VISCOUS PHOTONS AND LUMPY MUSIC

OUTLINE

- Sources & EM emissivity
- Modelling the evolving system:
  - 3D hydro
  - 3D viscous hydro
  - Fluctuating initial states
- Are photons sensitive to all of the above?
  - If so, can we quantify this?
  - Dileptons?

Charles Gale
McGill University

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INFO CARRIED BY THE RADIATION

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times\langle j\,|\,J_\mu\,|\,i\rangle\langle i\,|\,J_\nu\,|\,j\rangle$$

Thermal ensemble average of the current-current correlator

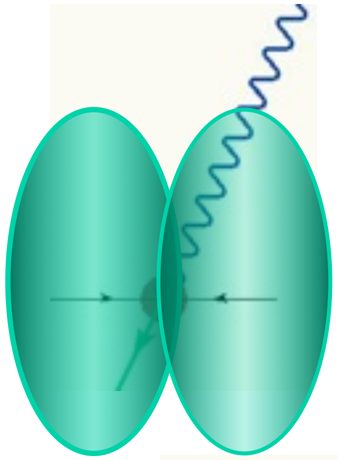
Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(photons)}$$

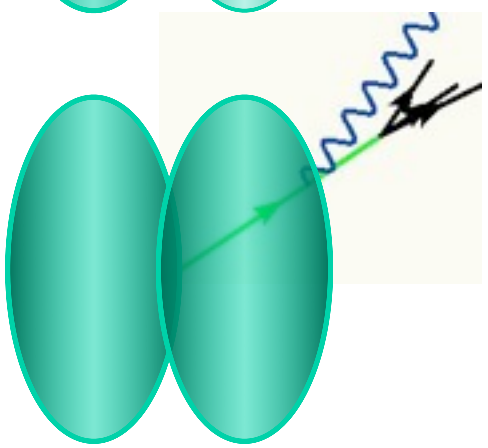
$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\,\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(dileptons)}$$

McLerran, Toimela (85), Weldon (90), Gale, Kapusta (91)

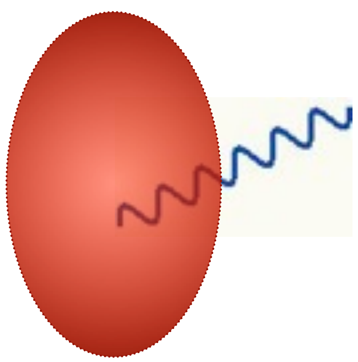
Sources of photons:



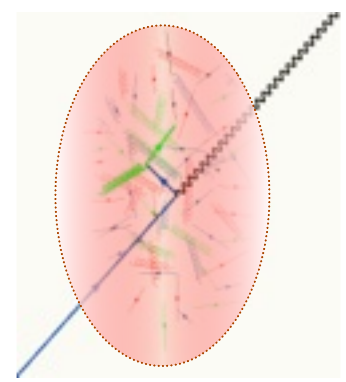
Hard direct photons. pQCD with shadowing
Non-thermal



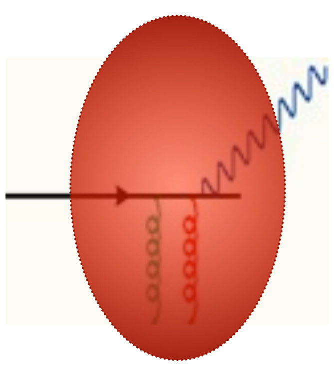
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal

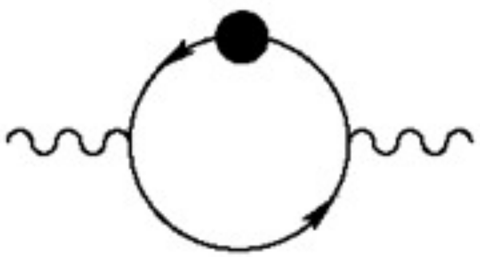


Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

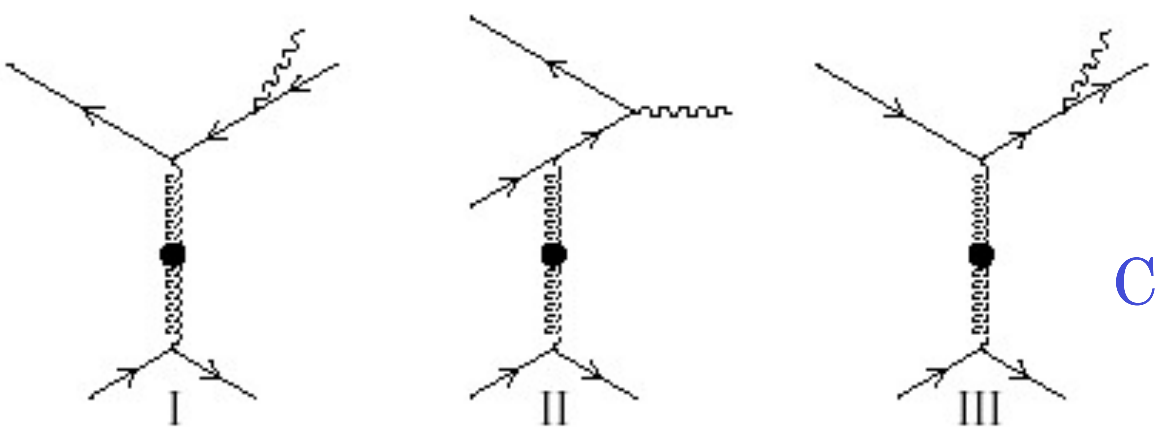
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



$$\mathrm{Im}\,\Pi^{\mu}_{R\mu} \sim \ln\left(\frac{\varpi T}{\left(m_{th}\left(\sim gT\right)\right)^{2}}\right)$$

Kapusta, Lichard, Seibert (1991)
Baier, Nakkagawa, Niegawa, Redlich (1992)

Going to two loops: Aurenche, Kobes, Gelis, Petitgirard (1996)
Aurenche, Gelis, Kobes, Zaraket (1998)



Co-linear singularities: $\alpha_s^2\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$

2001: Results complete at $O(\alpha_s)$

Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

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Charles Gale

ELECTROMAGNETIC RADIATION FROM HADRONS

Chiral, Massive Yang-Mills:

O. Kaymakcalan, S. Rajeev, J. Schechter, PRD 30, 594 (1984)

$$\mathcal{L} = \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, D_\mu U D^\mu U^\dagger + \frac{1}{8} F_\pi^2 \,\mathrm{Tr}\, \mathrm{M}\left(\mathrm{U} + \mathrm{U}^\dagger\right)$$

$$- \frac{1}{2} \mathrm{Tr}\left(F_{\mu\nu}^L F^{L\mu\nu} + F_{\mu\nu}^R F^{R\mu\nu}\right) + m_0^2 \mathrm{Tr}\left(A_\mu^L A^{L\mu} + A_\mu^R A^{R\mu}\right)$$

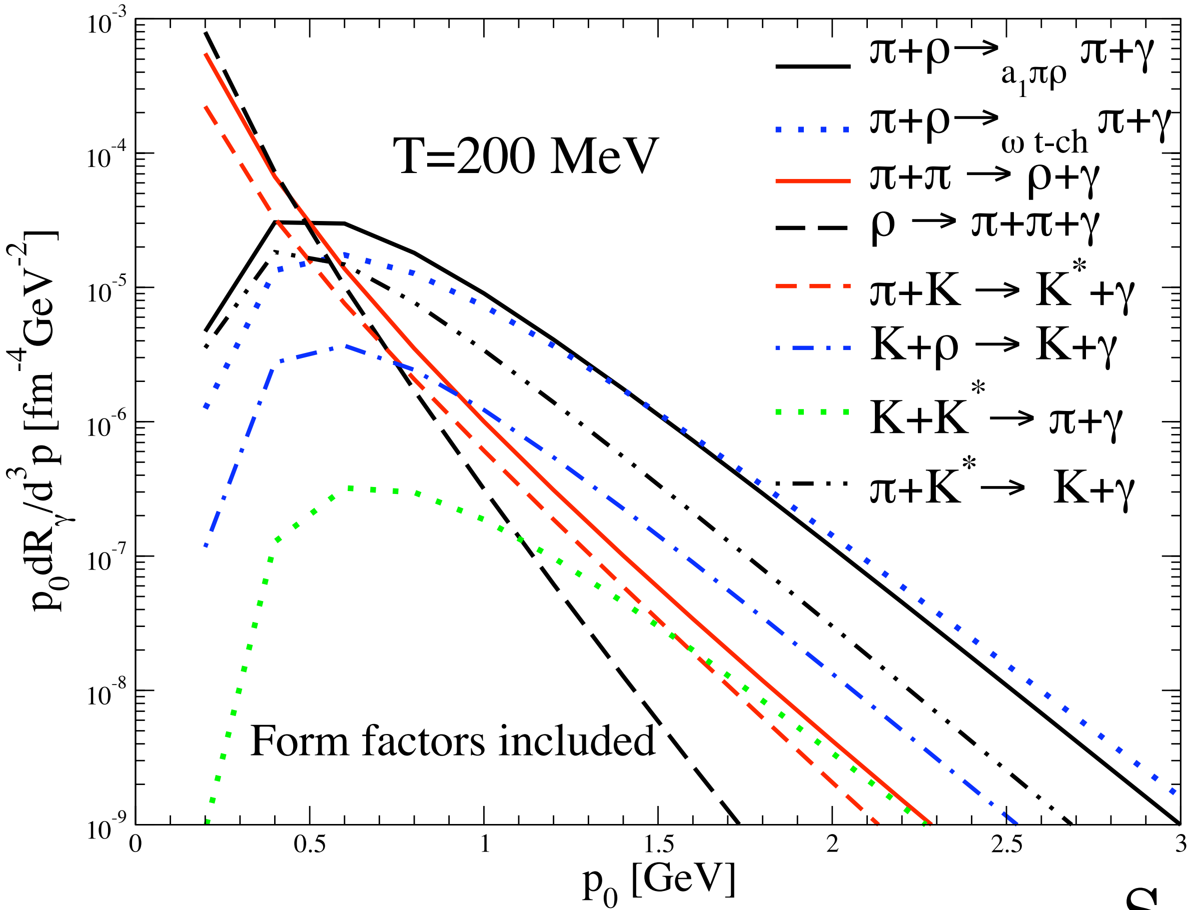
+ non-minimal terms

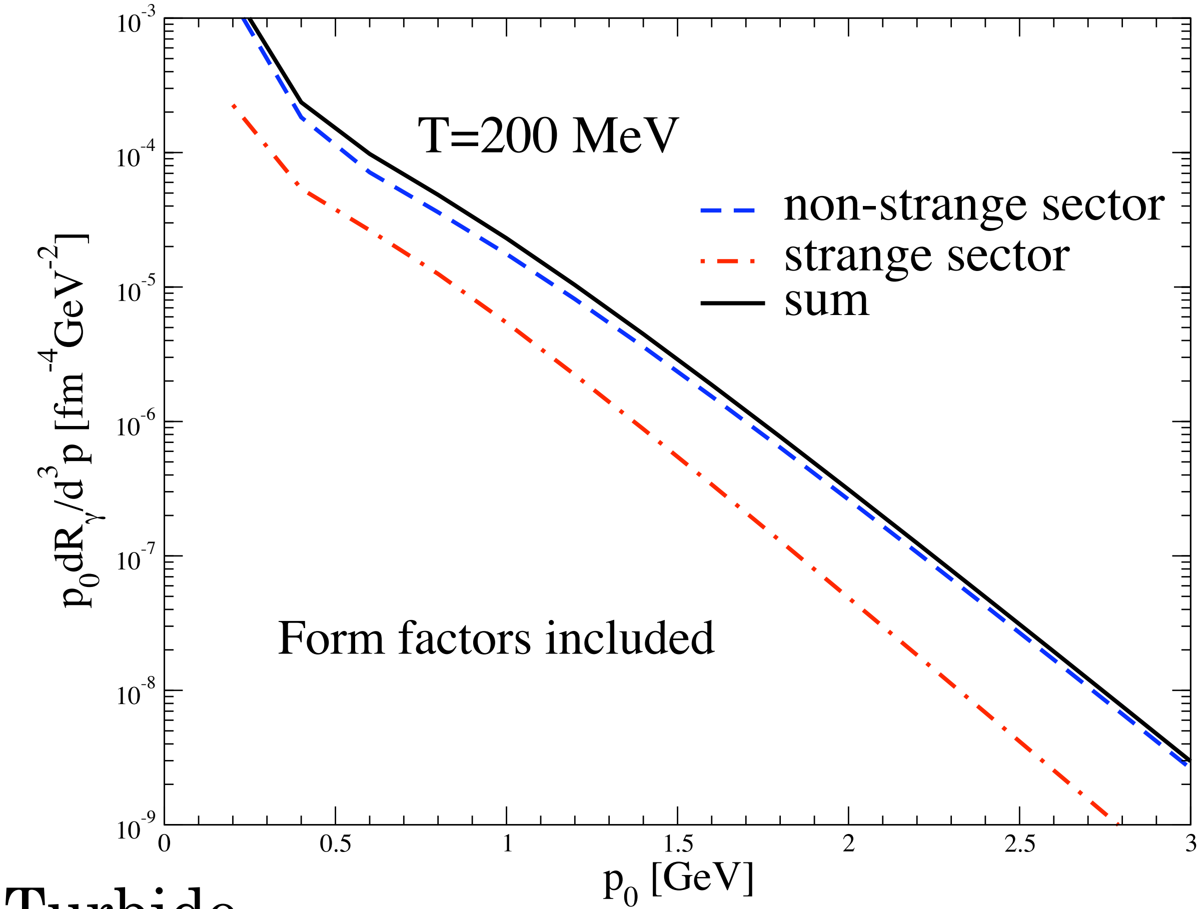
Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Other hadronic observables:
  - *e.g.* $a_1 \rightarrow \pi\rho \quad D/S$ (See also, Lichard and Vojik, arXiv:1006.2919)

EM emissivities computed: Turbide, Rapp, Gale, PRC (2004); Turbide, McGill PhD (2006)

Photon spectra: some results

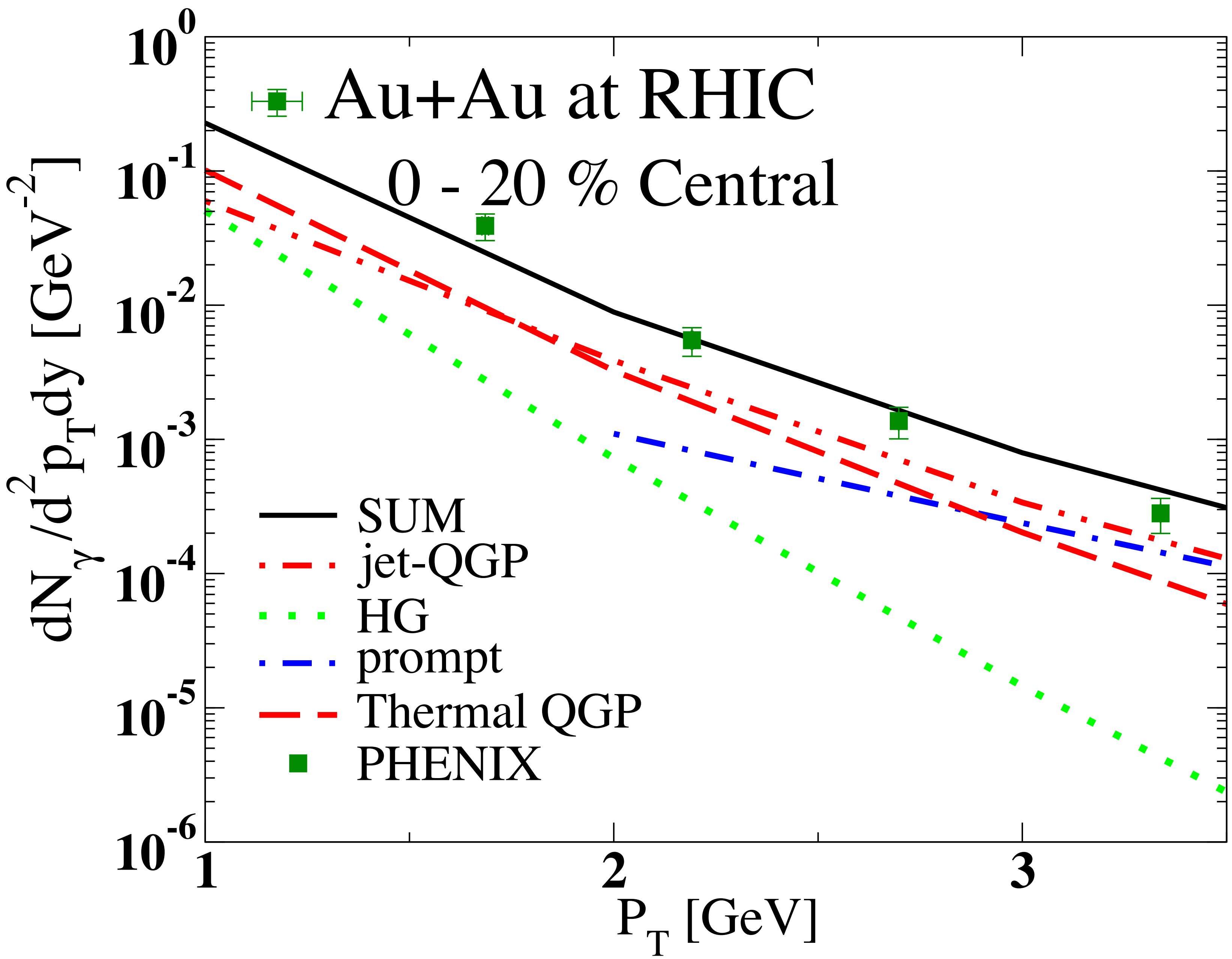




S. Turbide

- Reactions involving strangeness sub-dominant
- Large contribution from the hadronic channels with a $\pi\rho$ initial state
- Used to interpret WA98 data

Applying this to the soft sector @ RHIC

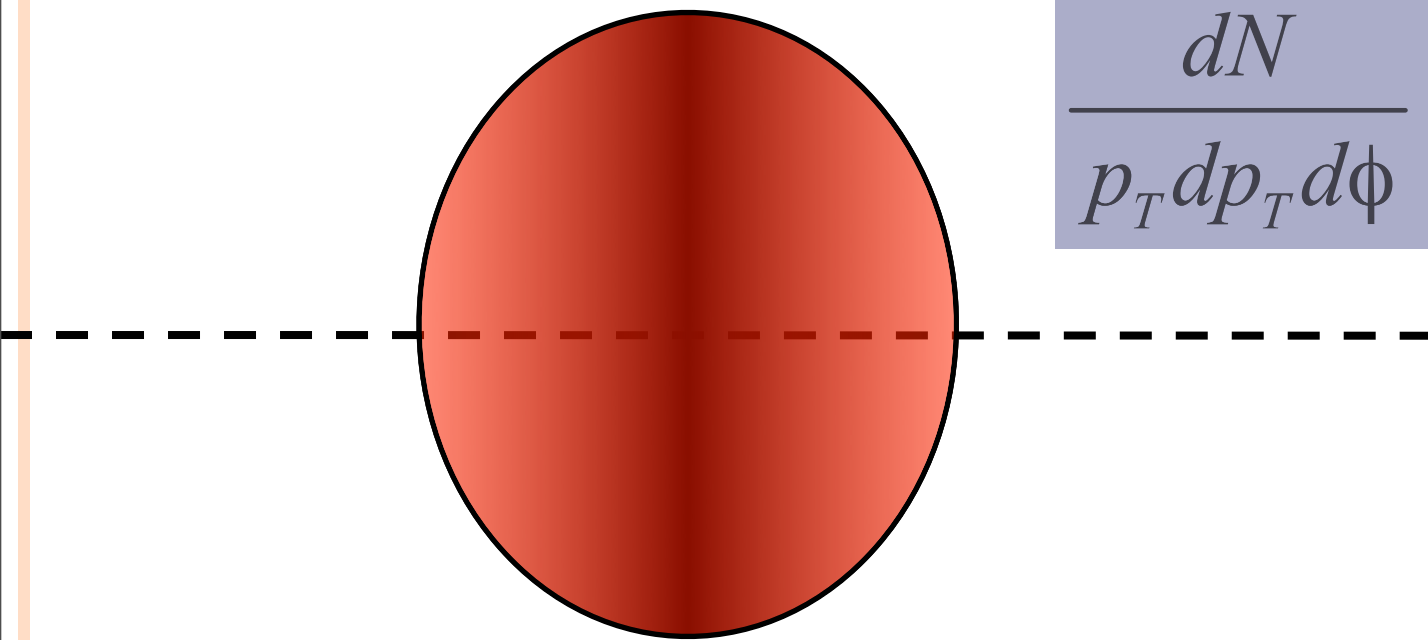


- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for jet-QPG contributions at mid-p_T

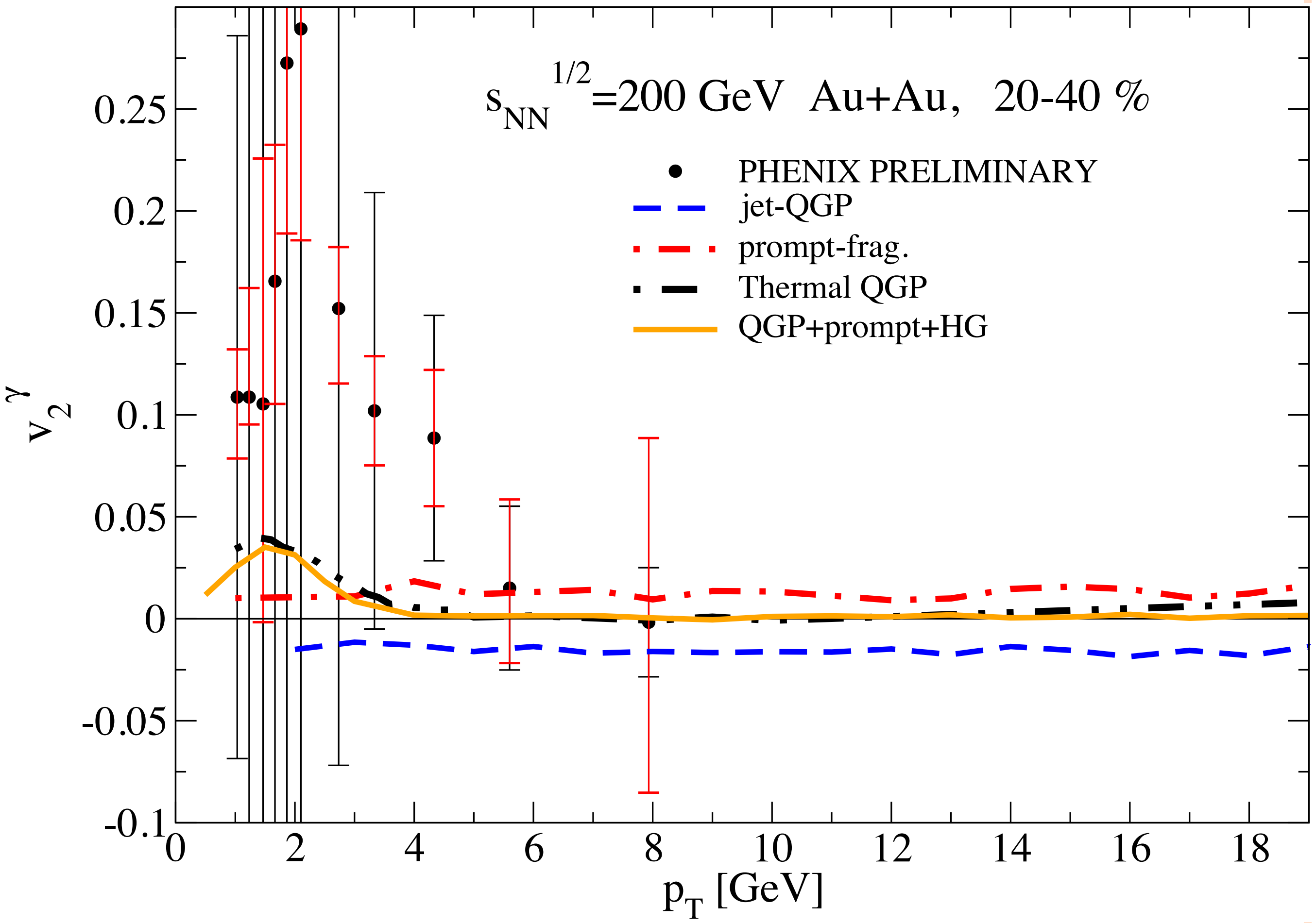
Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

BEYOND ONE-BODY DATA: FLOW AND CORRELATIONS

$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2v_n \cos(n\phi)\right]$$



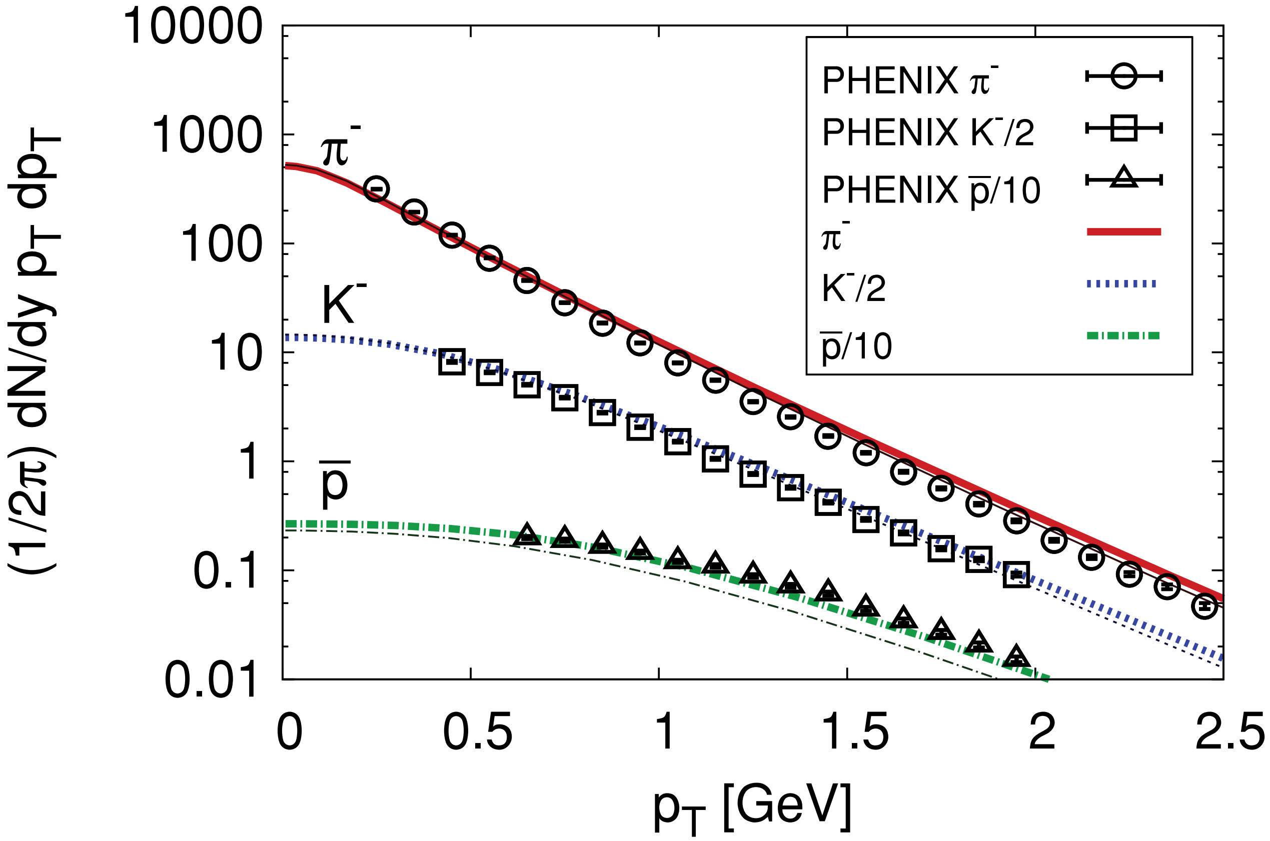
- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- Details will matter: flow, T(t). . .

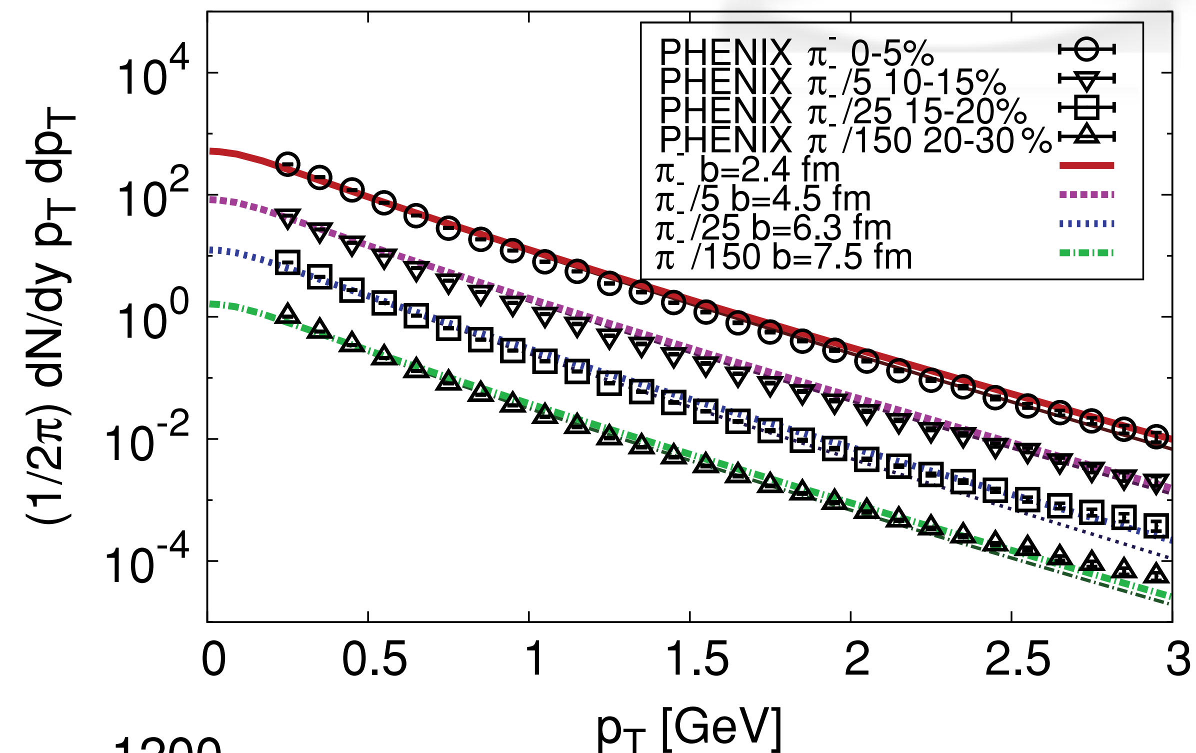


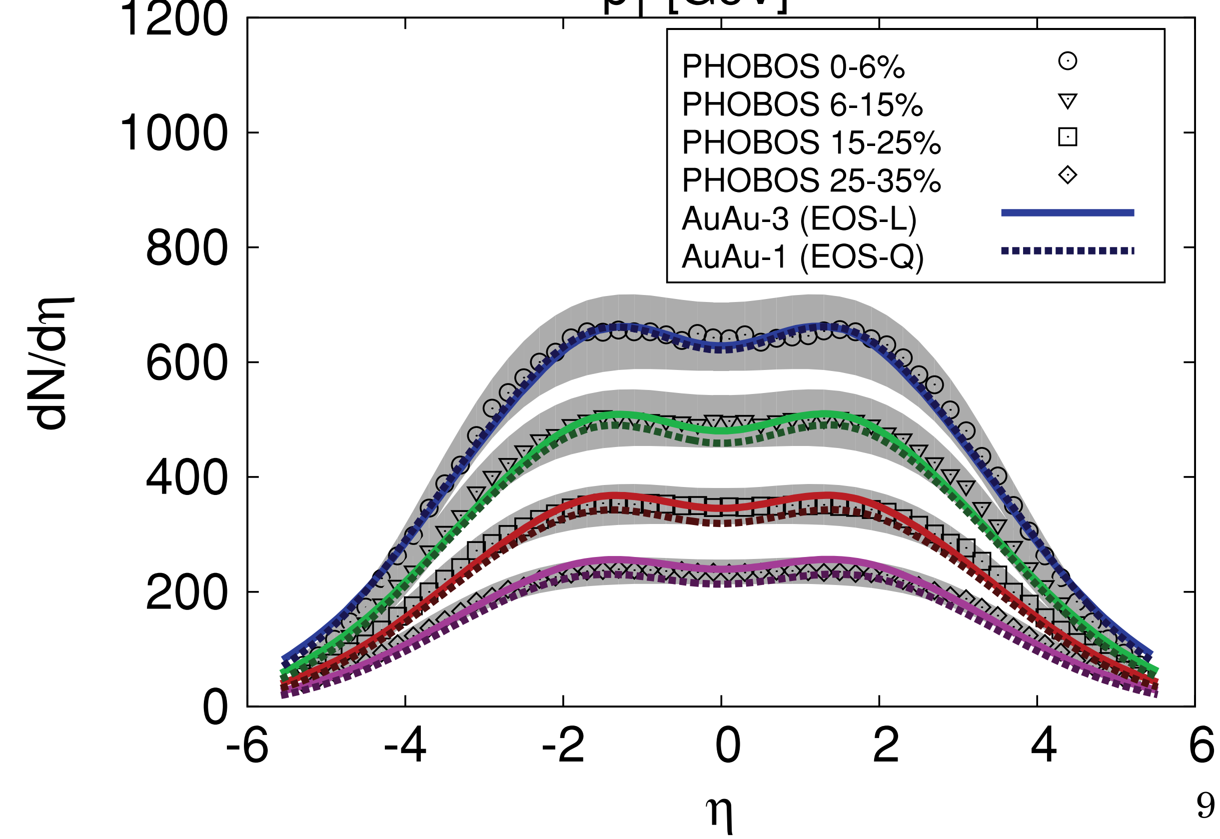
Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

3D Relativistic Hydrodynamics:

MUSIC:







- MUSIC: 3D relativistic hydro
  - Ideal: Schenke, Jeon, and Gale, PRC (2010)
  - FIC and Viscous: Schenke, Jeon, Gale, PRL (2011)

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The effects of shear viscosity on bulk dynamics

$$T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu}$$

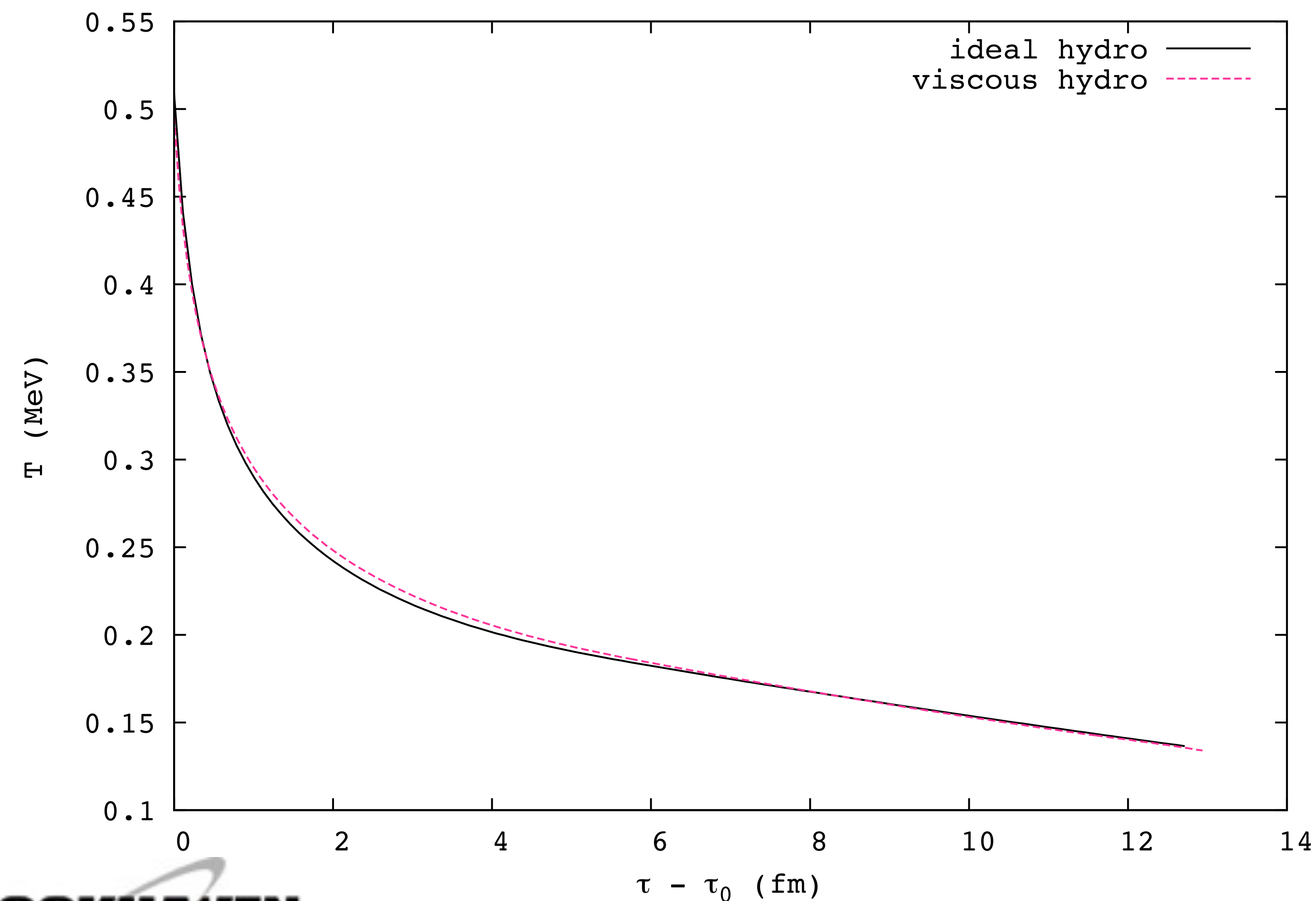
$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu}$$

Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

$$\partial_{\mu} T^{\mu\nu} = 0, \quad \Delta^{\mu}_{\alpha}\Delta^{\upsilon}_{\beta} u^{\sigma}\partial_{\sigma}\pi^{\alpha\beta} = -\frac{1}{\tau_{\pi}}(\pi^{\mu\upsilon} - S^{\mu\upsilon}) - \frac{4}{3}\pi^{\mu\upsilon}(\partial_{\alpha}u^{\alpha})$$

$$\partial_{\mu}(su^{\mu}) \propto \eta$$

(c.f. Talk by B. Schenke)



- Viscous evolution starts with a lower T
- T drop is slower than ideal case

The effects of shear viscosity on bulk dynamics

$$T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu}$$

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Israël & Stewart, Ann. Phys. (1979), Baier et al., JHEP (2008), Luzum and Romatschke, PRC (2008)

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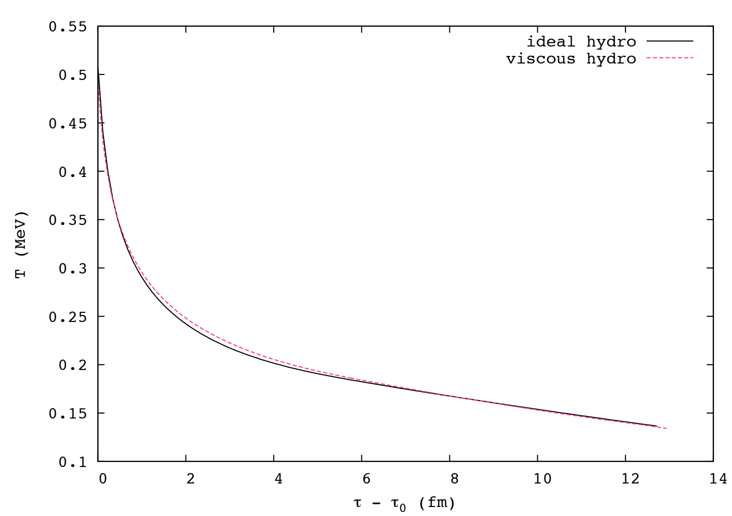
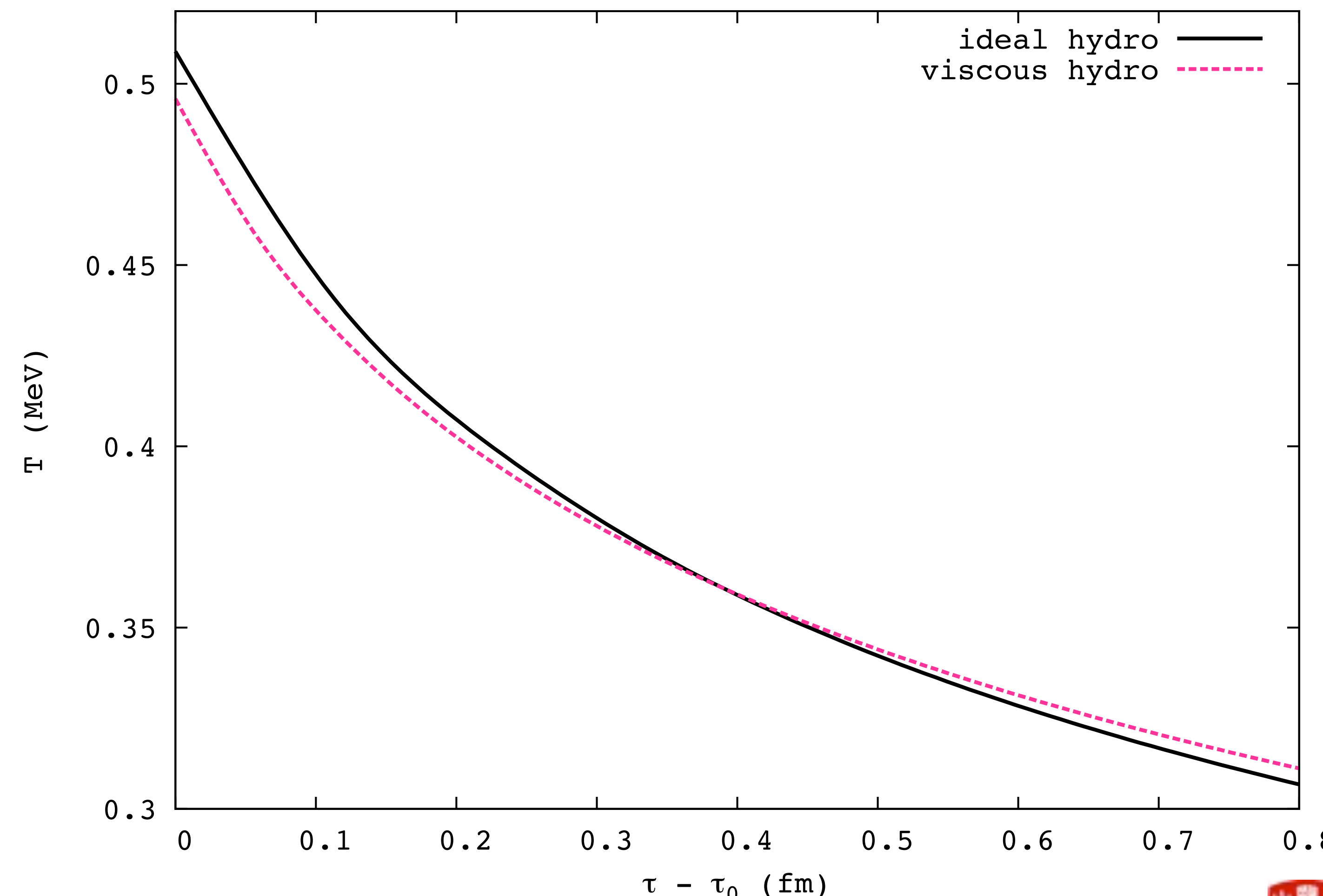
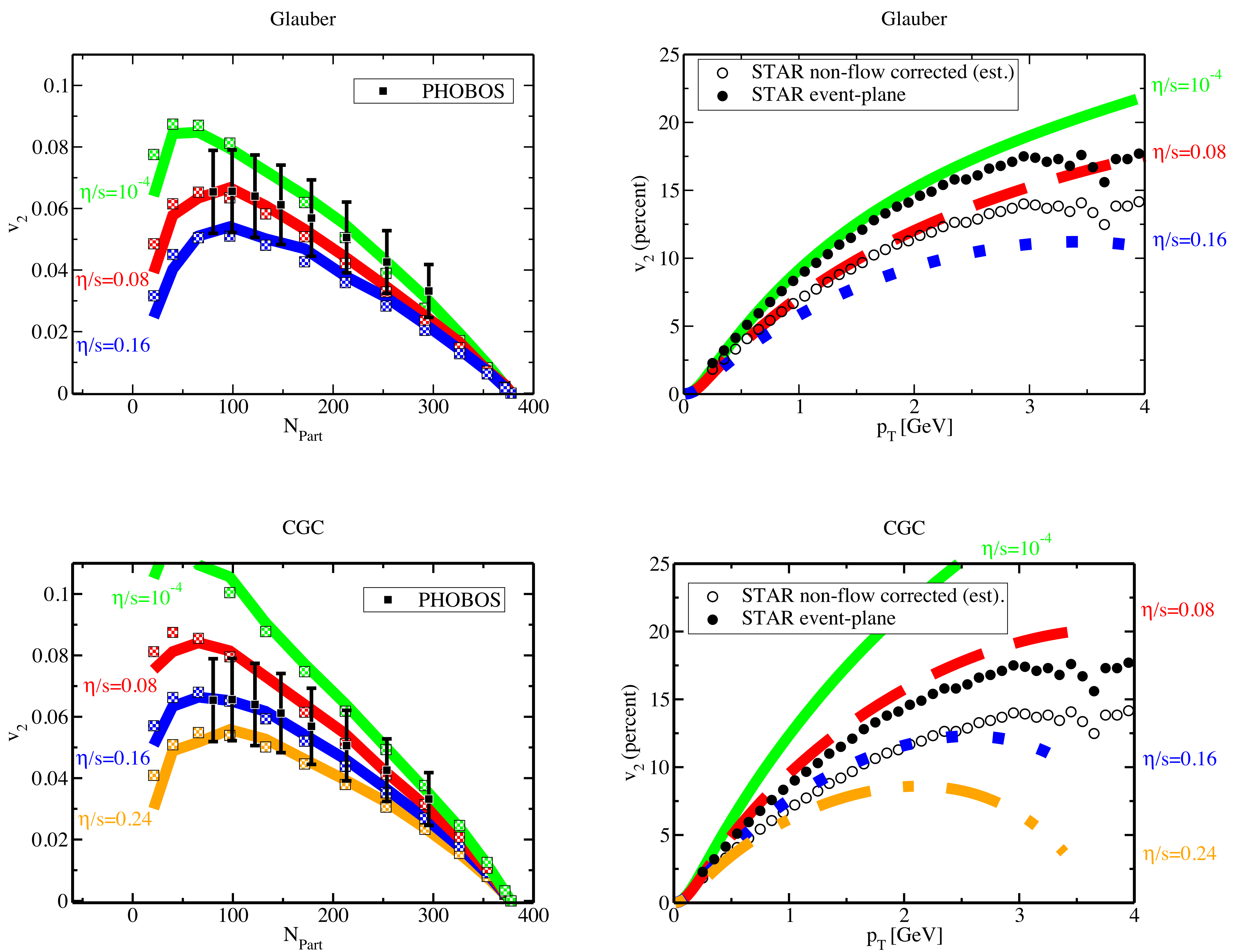




MOVING INTO THE "CHARACTERIZATION" PHASE...



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Luzum & Romatschke, PRC (2009)

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THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

$$f \to f_0 + \delta f, \quad \delta f = f_0 (1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P) T^2}$$

$$q_0 \frac{d^3 R}{d^3 q} = \int \frac{d^3 p_1}{2(2\pi)^3 E_1} \frac{d^3 p_2}{2(2\pi)^3 E_2} \frac{d^3 p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1) f(E_2)\left[1 \pm f(E_3)\right]}{2(2\pi)^3}$$

One considers all the reaction and radiative decay channels of external state combinations of:

$\{\pi, K, \rho, K^*, a_1\}$ With hadronic form factors

+ QGP Photons

THE EFFECTS OF SHEAR VISCOSITY ON THE PHOTON DISTRIBUTION

In-medium **hadrons**:

Ansatz: Dusling, Moore, Teaney PRC (2010)

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

$$f \to f_0 + \delta f, \quad \delta f = f_0 (1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

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One considers all the reaction and radiative decay channels of external state combinations of:

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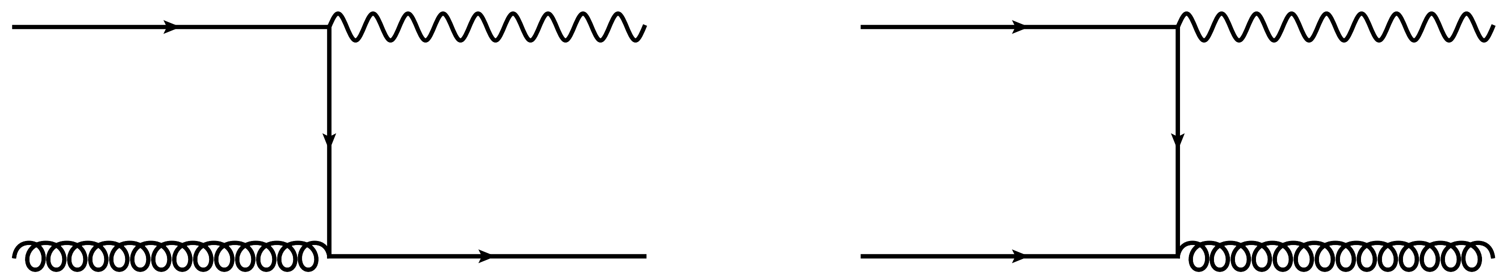
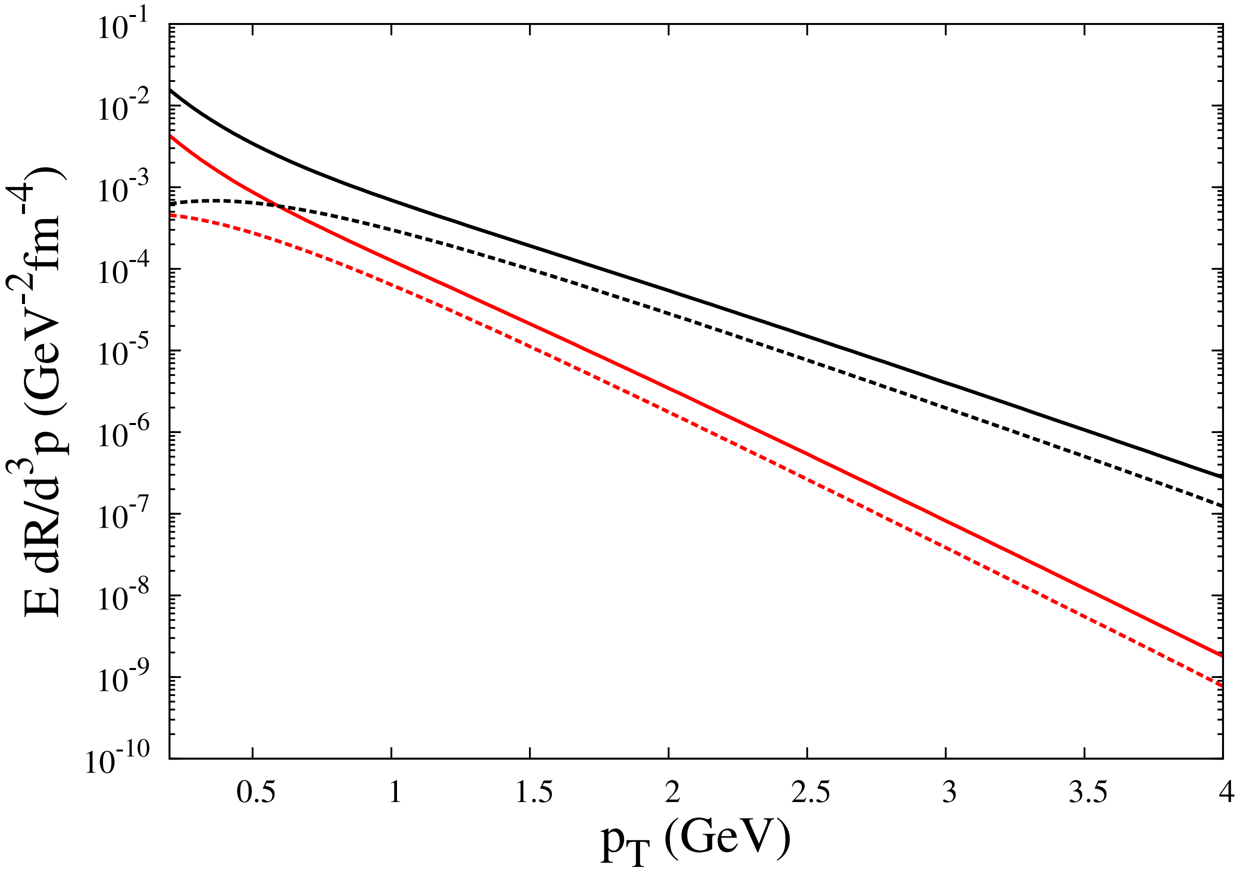
The QGP photons here:



$$E\frac{d^3R}{d^3p} = \sum_i \frac{N}{(2\pi)^7}\frac{1}{16E}\int ds\, dt\, |M|^2 \int dE_1\, dE_2 f_1(E_1) f_2(E_2)[1 \pm f_3(E_1+E_2-E)]$$

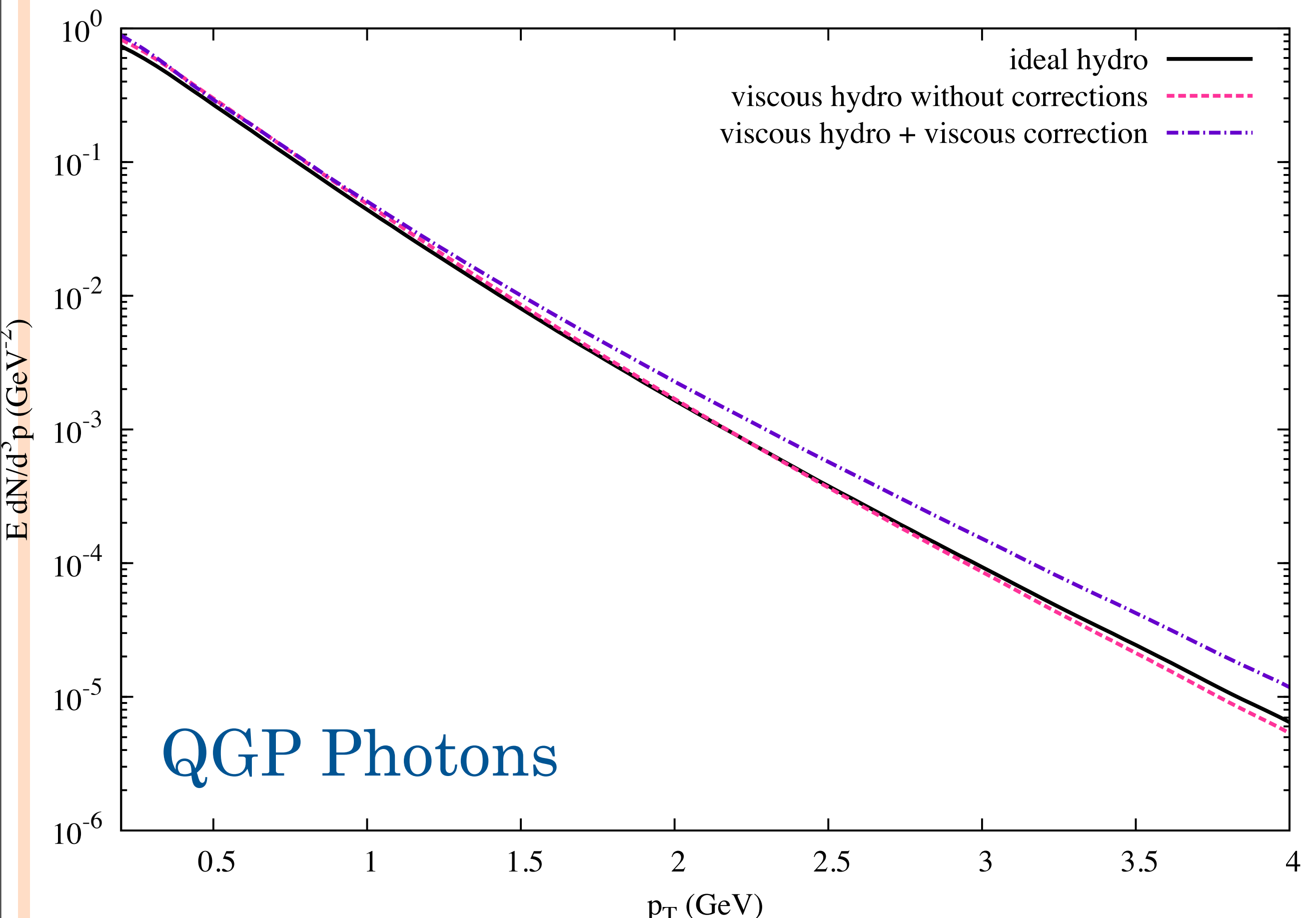
$$\times \frac{\theta(E_1+E_2-E)}{\sqrt{(aE_1^2+bE_1+c)}}$$

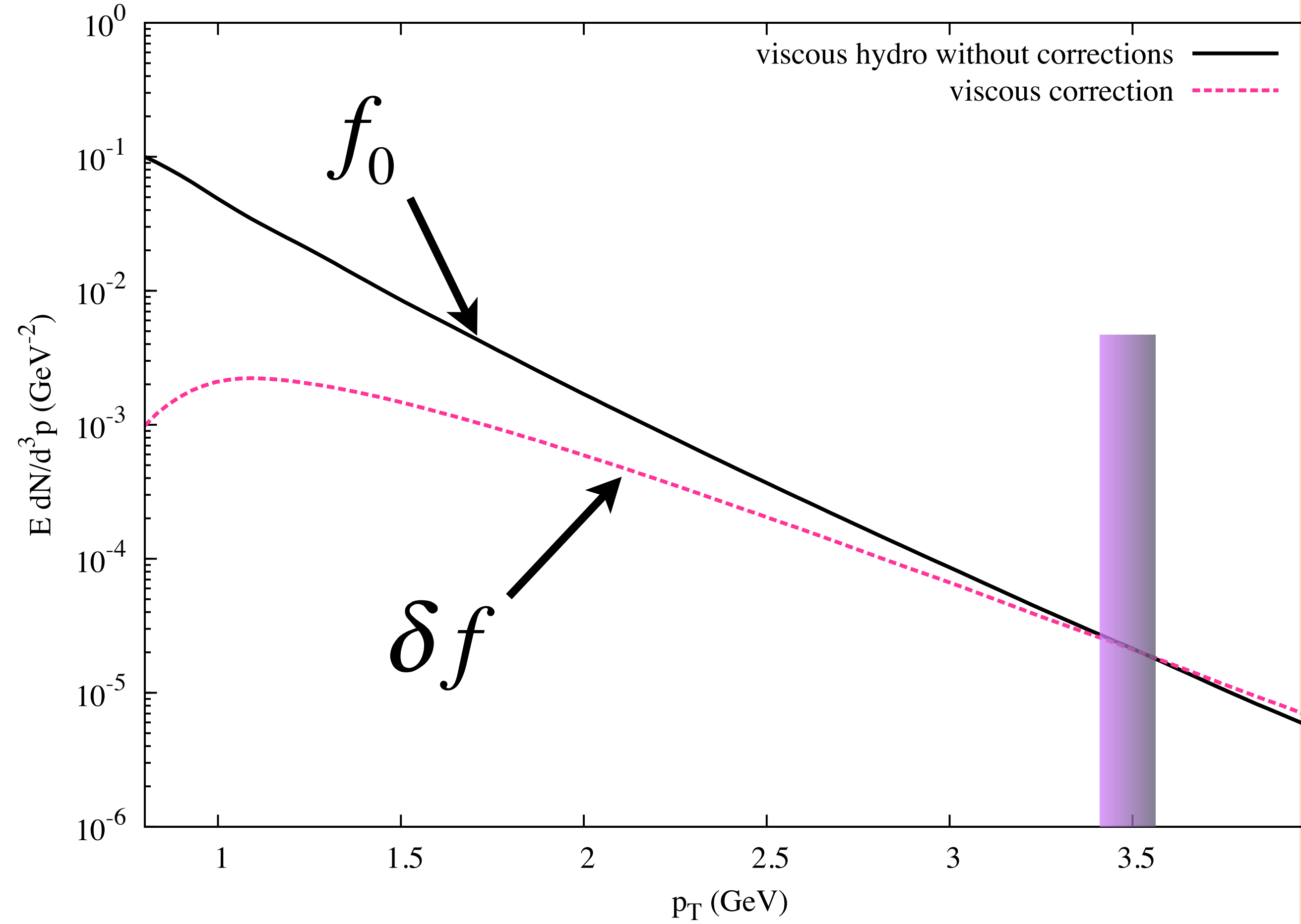


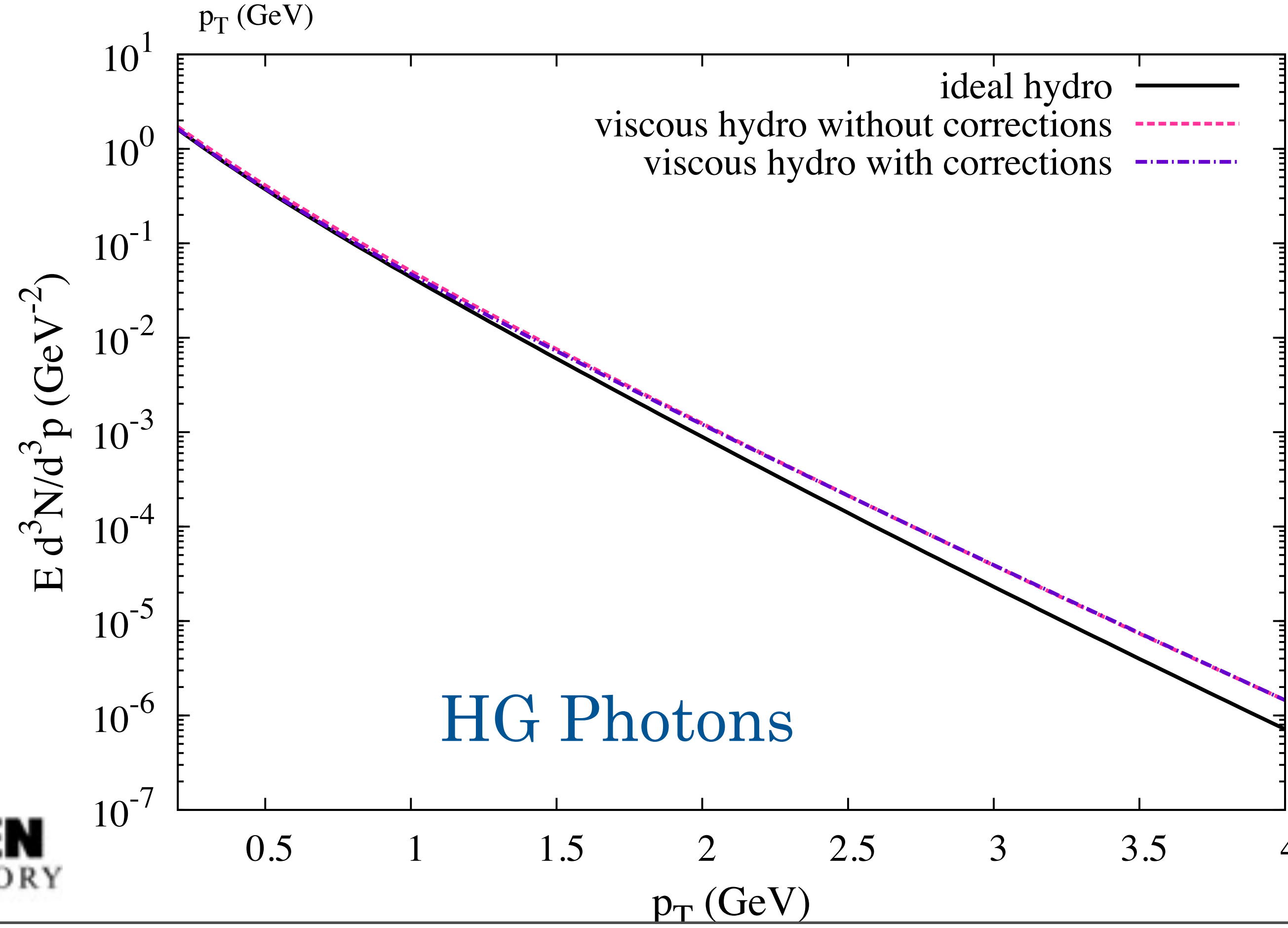
- Difference between C+a and leading order rates is ≈2, past 1 GeV
- $N_f = 3$, T = 350 MeV (top), T = 250 MeV (bottom)

Dion *et al.*, PRC (2011)

The effects of shear viscosity on the photon distribution





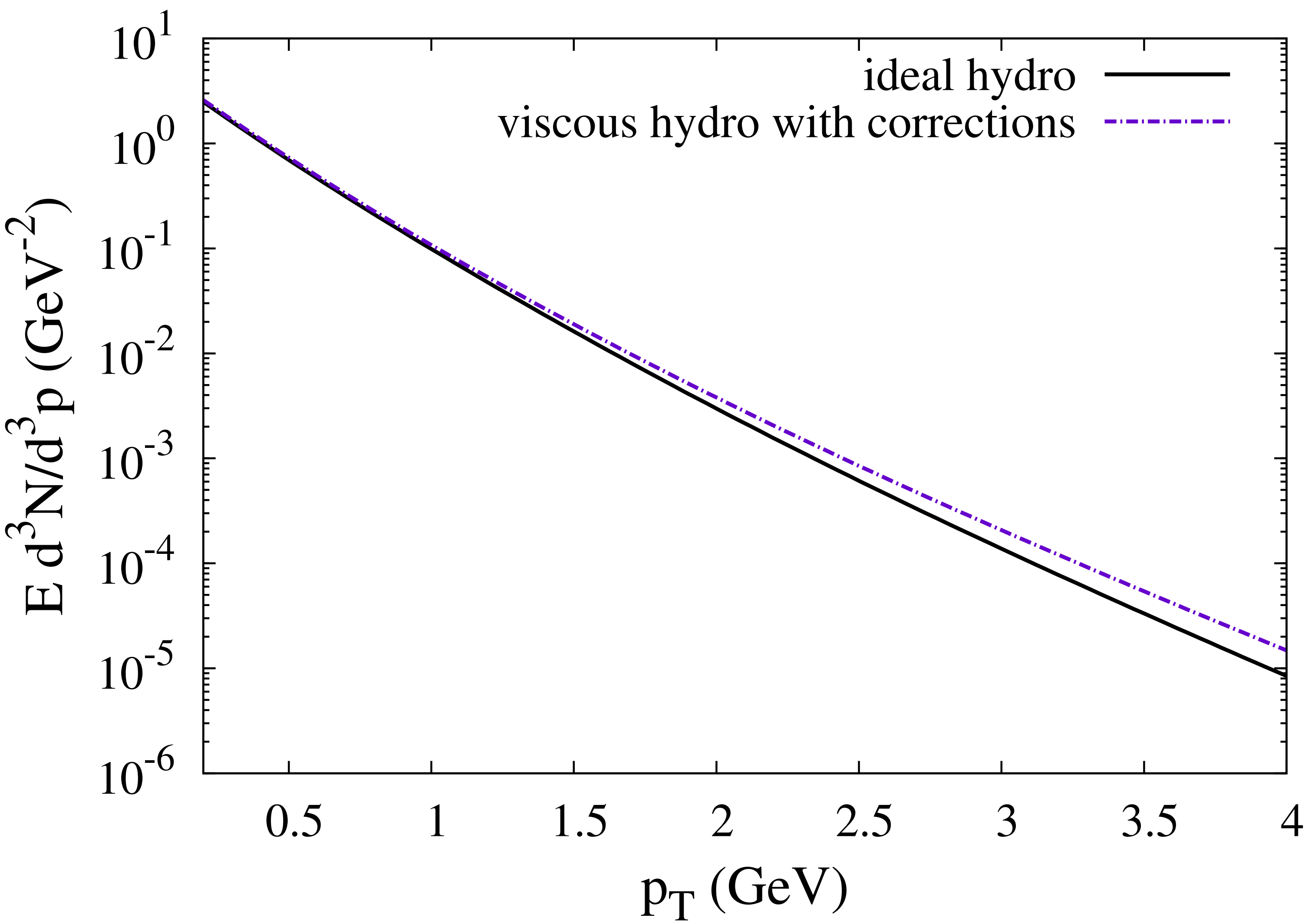


K. Dusling, NPA (2010)
Chaudhuri & Sinha, PRC (2011)

Viscous effects harden the photon spectrum

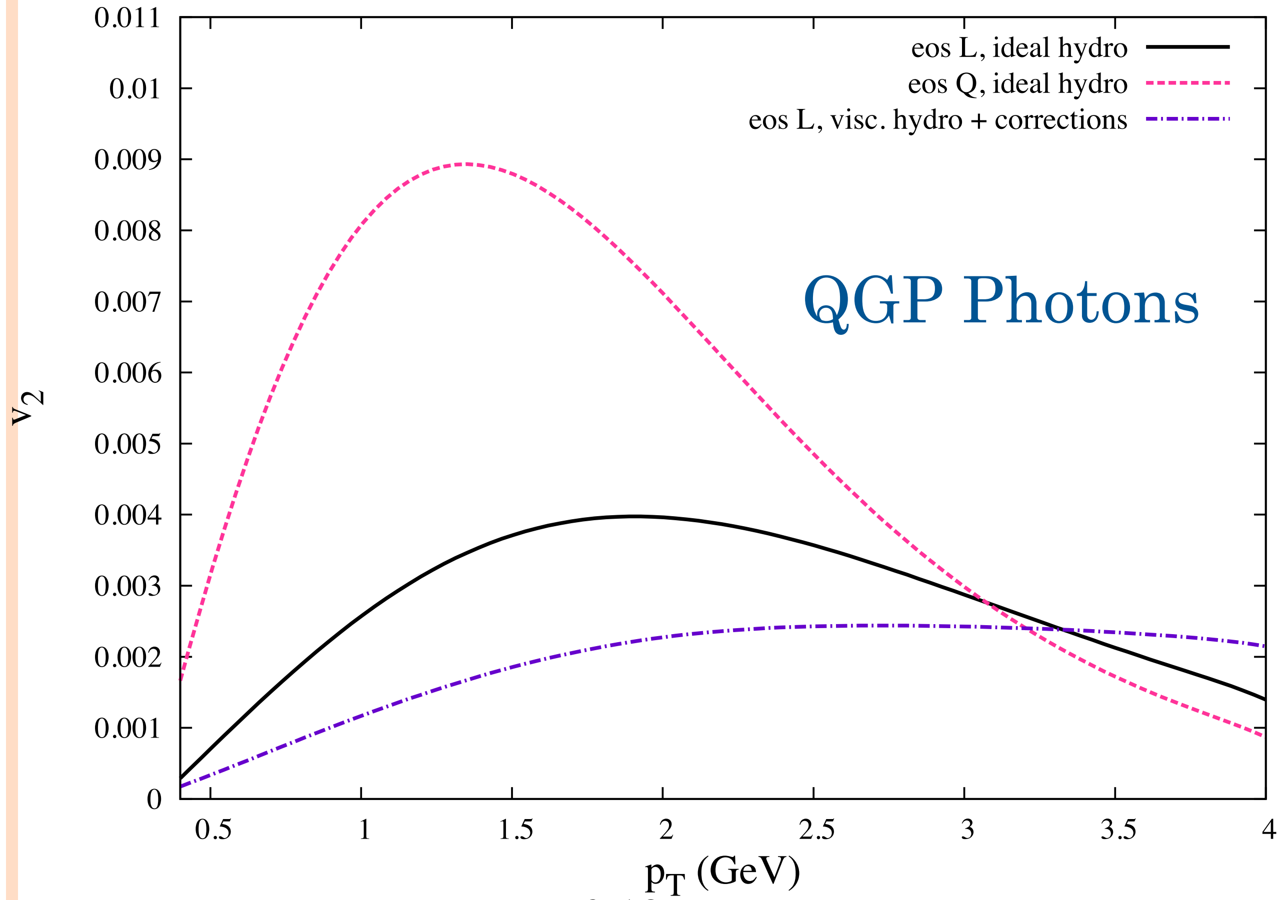
M. Dion, 2011

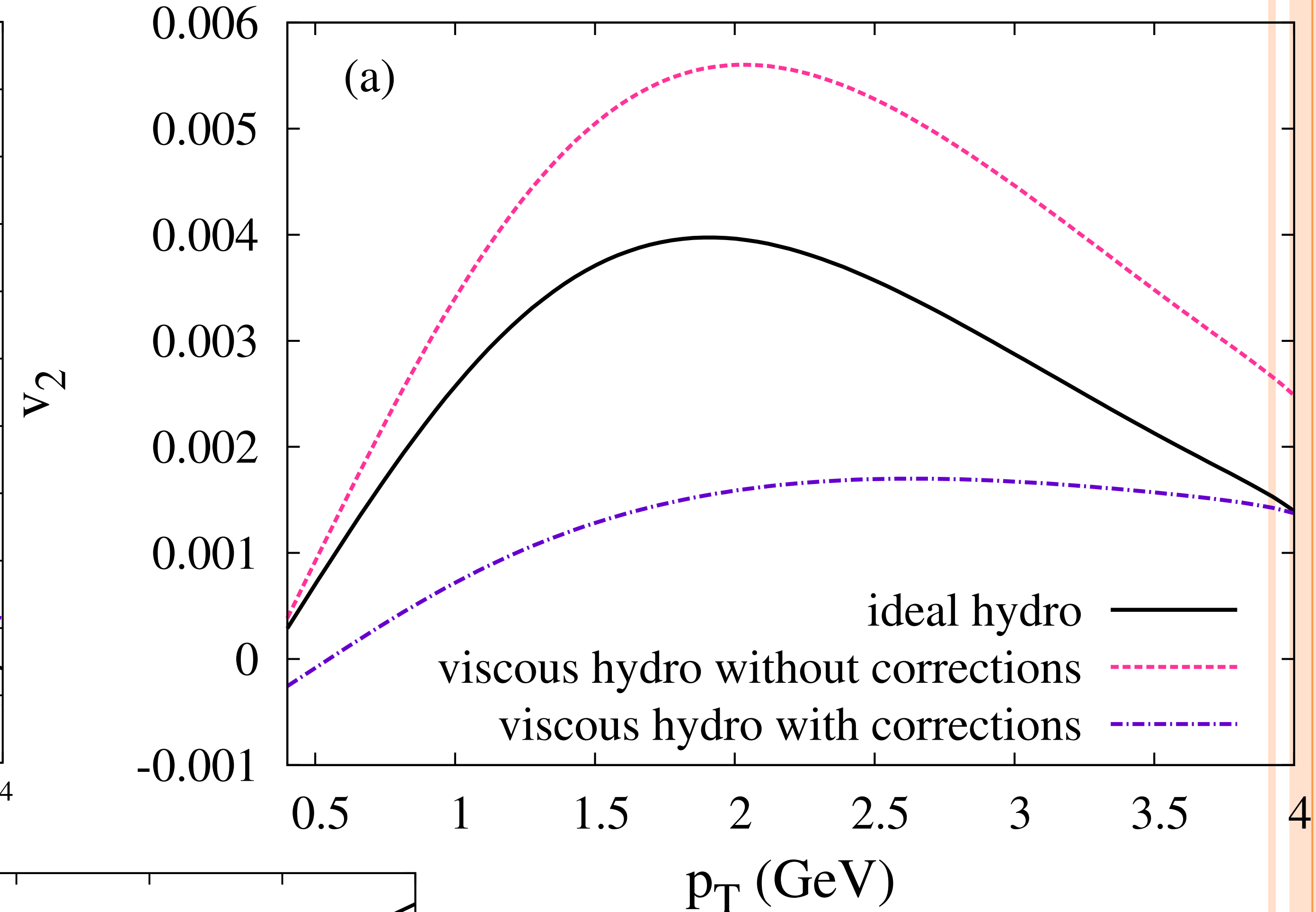
The net photon yield

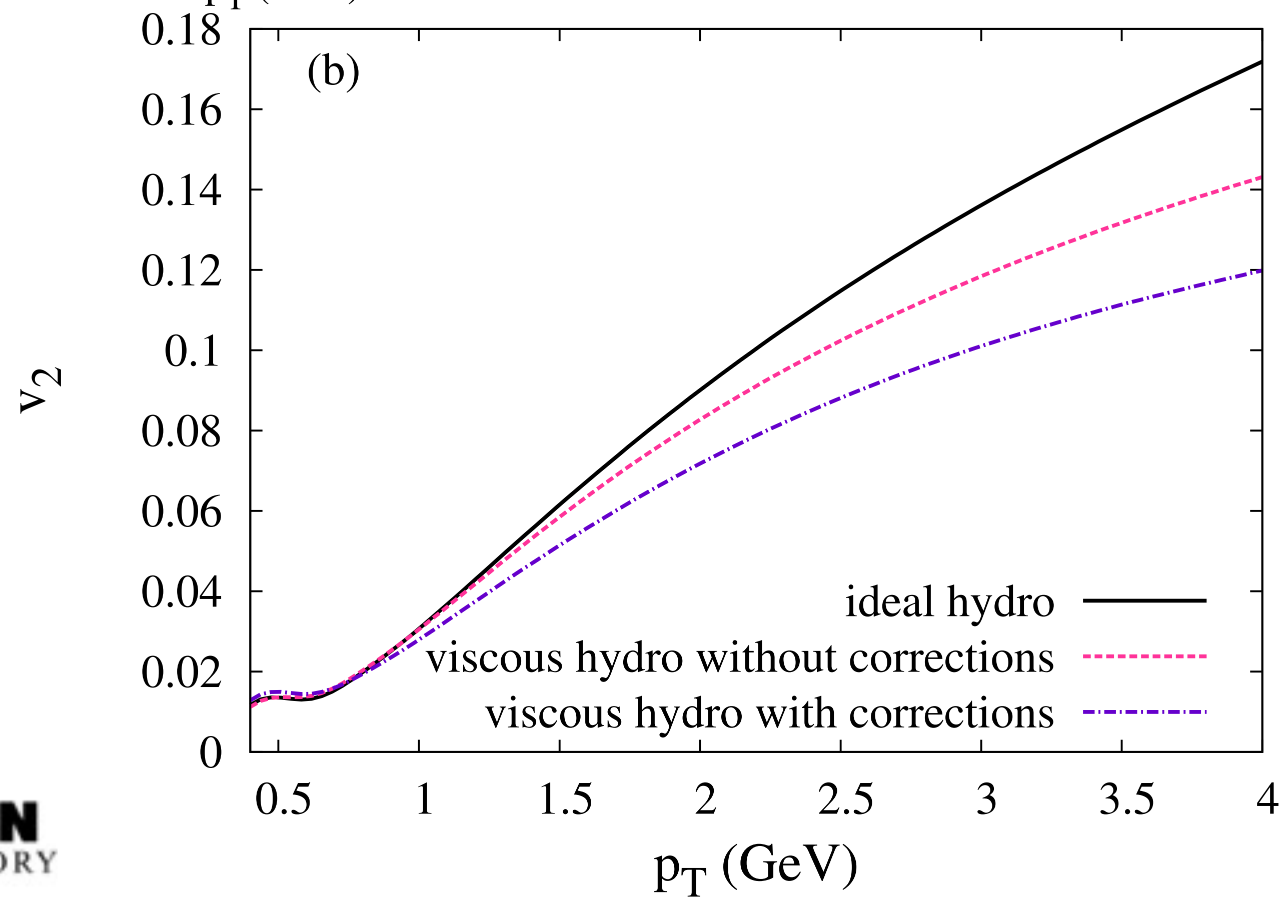


- Viscous corrections make the spectrum harder, by a modest amount (≈100% at p_T = 4 GeV).
- Extracting the viscosity from the photon spectra will be challenging
- More work is needed to properly include all photon sources in a consistent way

The effects of the EOS and of shear viscosity on (QGP) photon v_2



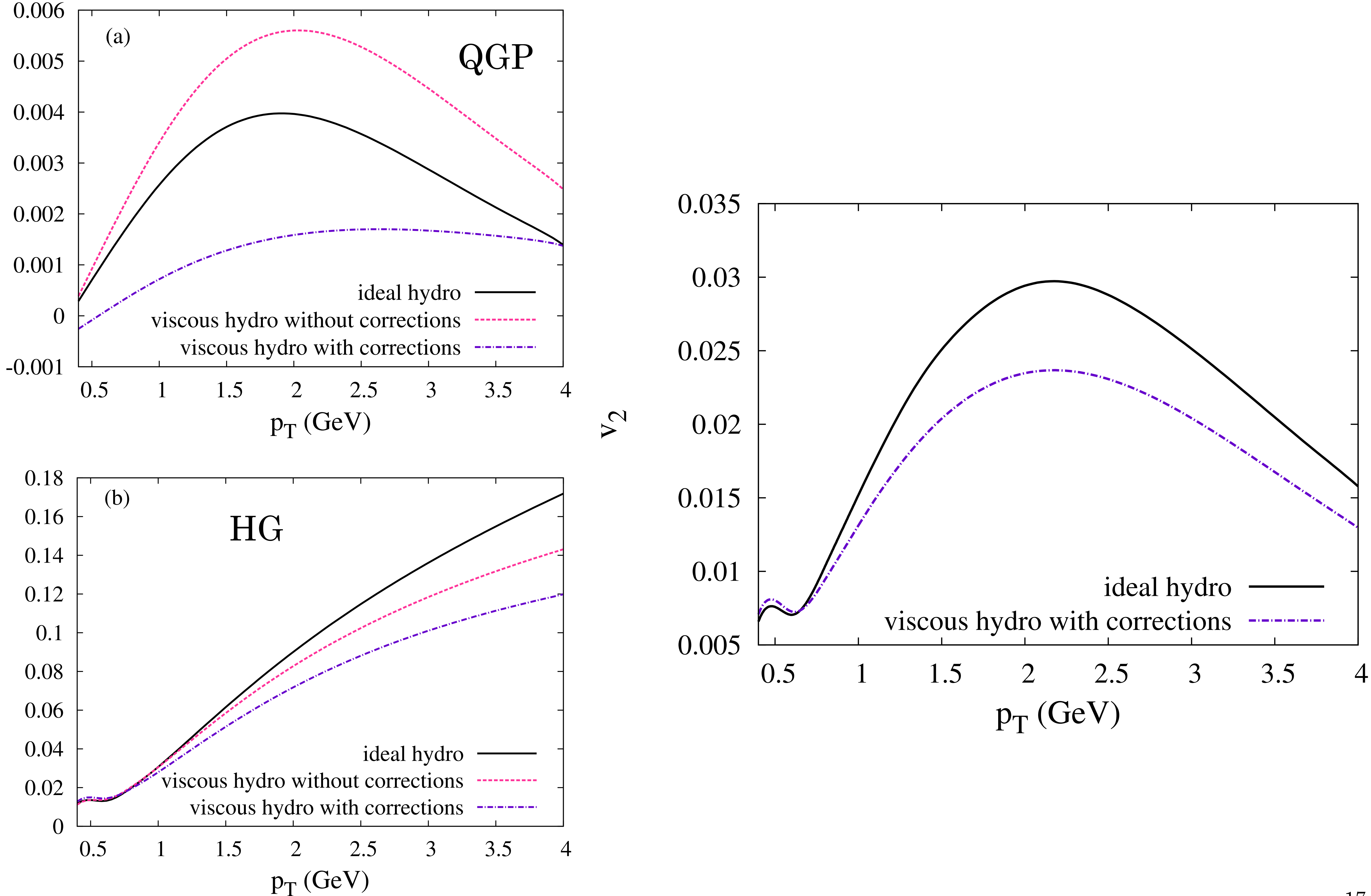




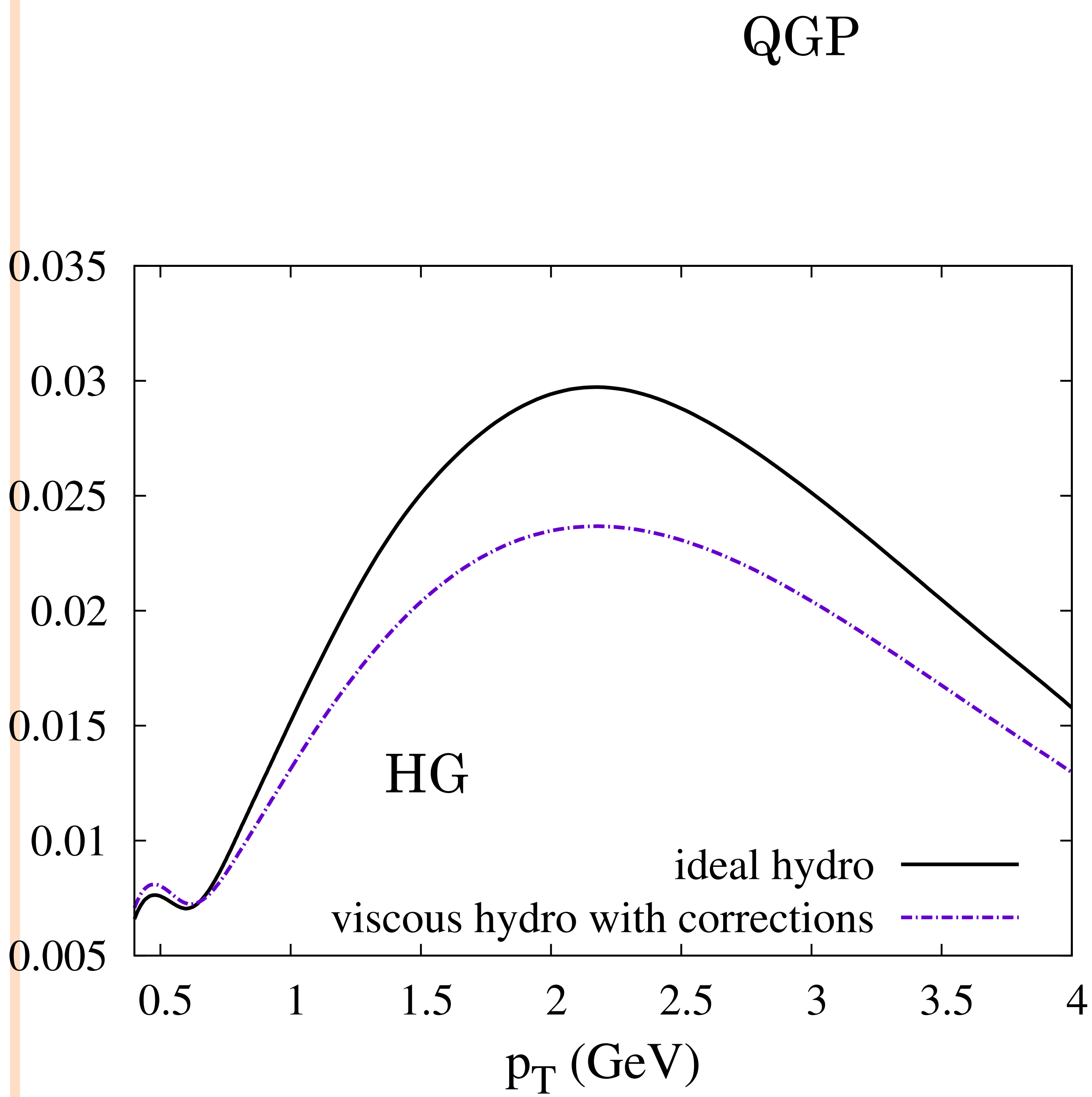
HG Photons

M. Dion, 2011

THE NET PHOTON V_2

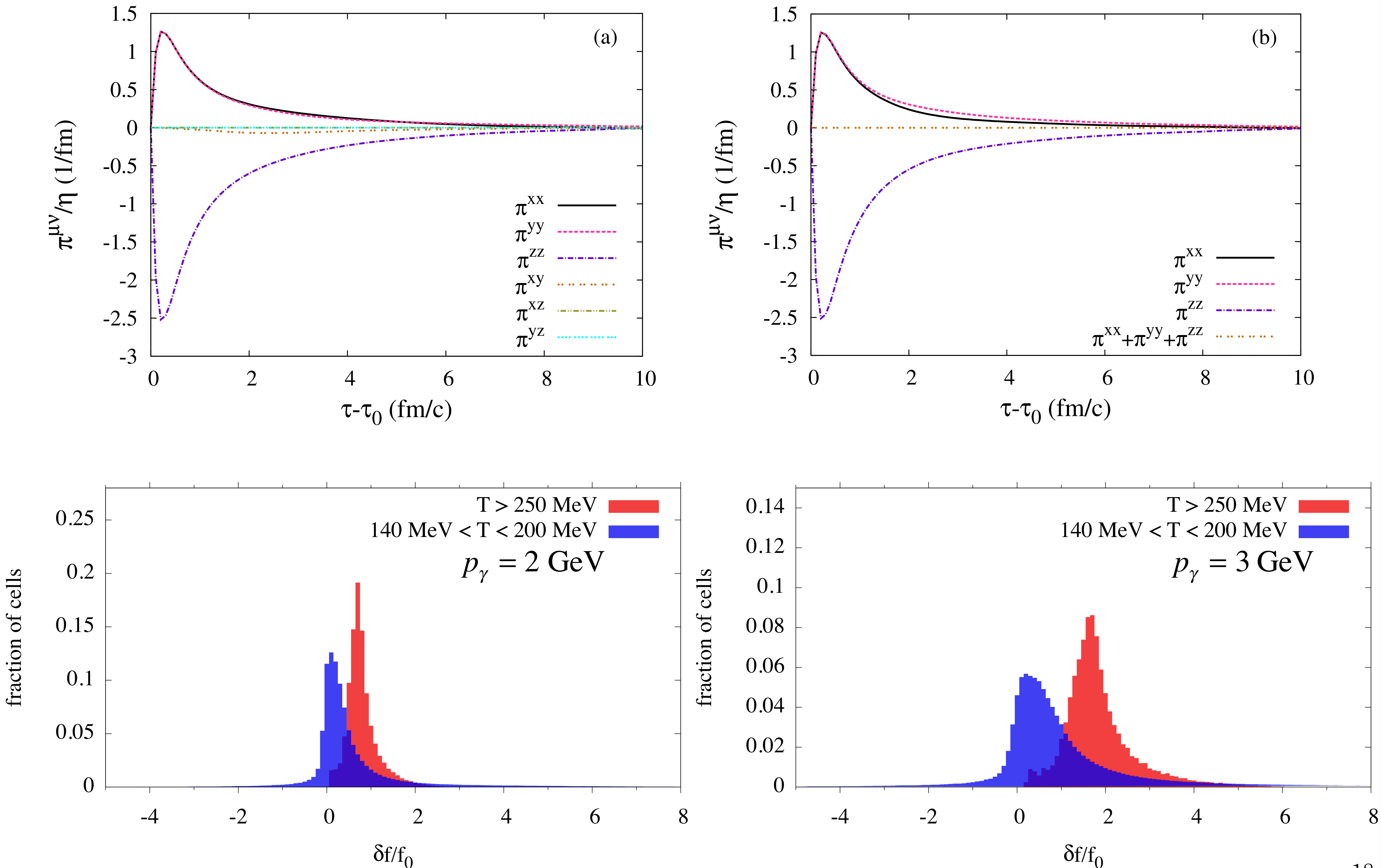


THE NET PHOTON V_2



- The net elliptic flow is a *weighted average*. A larger yield (QGP) will get compensated by a smaller v_2. Same story for the HG
- The turnover at $p_T \approx 2$ GeV is QGP-driven
- The small structure at low p_T is hadronic: it is a cross-over between two hadronic channels
- The net effect of viscous corrections makes the photon elliptic flow smaller, as it does for hadrons

Non-equilibrium effects



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NON-EQUILIBRIUM EFFECTS: CONT'D

- Pick a photon momentum ($\pi / 4$ in x-y plane, $\eta_s \approx 0$), Lorentz-transform back to fluid rest frame.
- Assume a massless fermion for the high T part. Processes are 2 $\rightarrow$2: Obtain the correction to the distribution function.
- Some numbers:

$\dfrac{\delta f}{f_0}$	Early times		Late times	
p_T = 2 GeV	≥ 1	$\approx 20\%$	≥ 1	$\approx 5\%$
	≥ 2	~ 0	≥ 2	$= 0$
p_T = 3 GeV	≥ 1	$\approx 80\%$	≥ 1	$\approx 25\%$
	≥ 2	$\approx 30\%$	≥ 2	$\approx 5\%$

- *Initially*, corrections vanish.

Non-equilibrium effects: cont'd

- Pick a photon momentum ($\pi / 4$ in x-y plane, $\eta_s \approx 0$), Lorentz-transform back to fluid rest frame.
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Photons probe the dynamics of the entire time-evolution

Non-equilibrium effects: cont'd

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Photons probe the dynami Caution , the entire time-evolution

Charles Gale

Anatomy of non-equilibrium effects

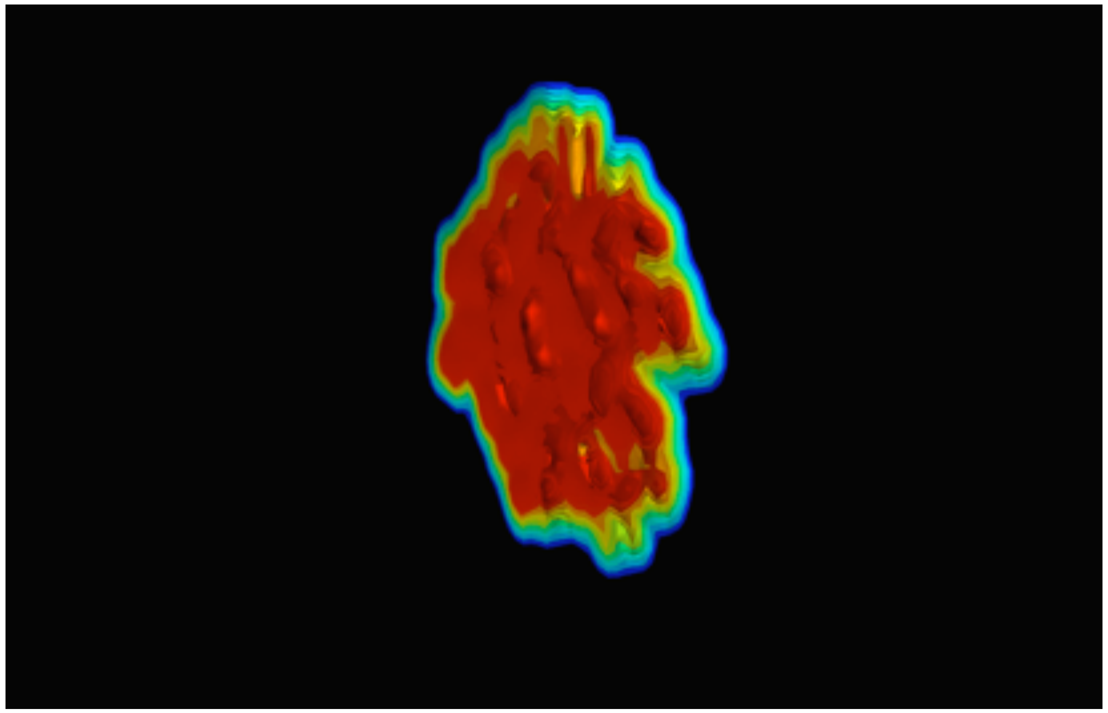
- Larger viscous corrections at high temperatures/early times: elements of the shear tensor are larger
- Higher momenta command larger viscous corrections: broader distribution for the relative correction factor
- Small (negligible number of occurrences where the occupation function becomes negative

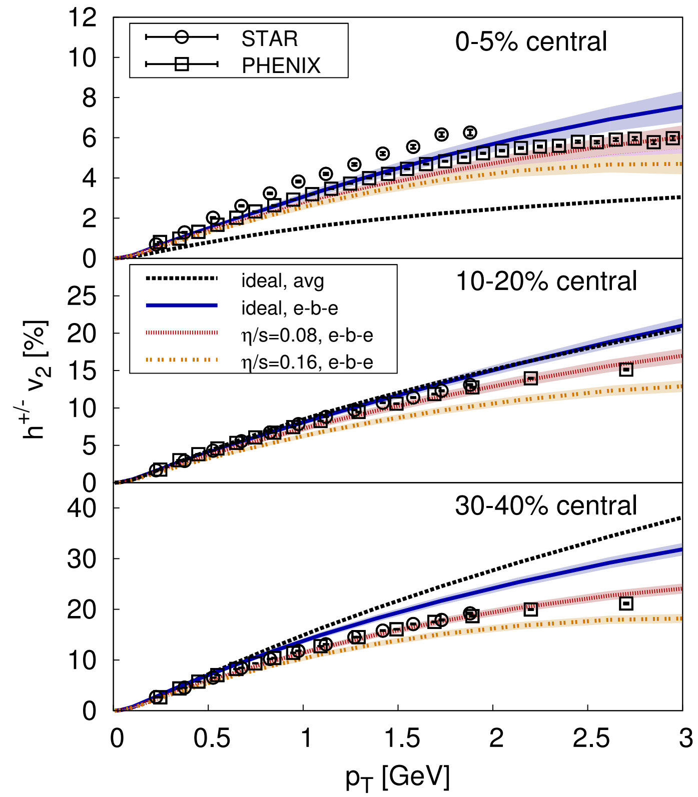
- <u>Only electromagnetic radiation</u> imposes such a stringent constraint on the dynamical models: from early to late times

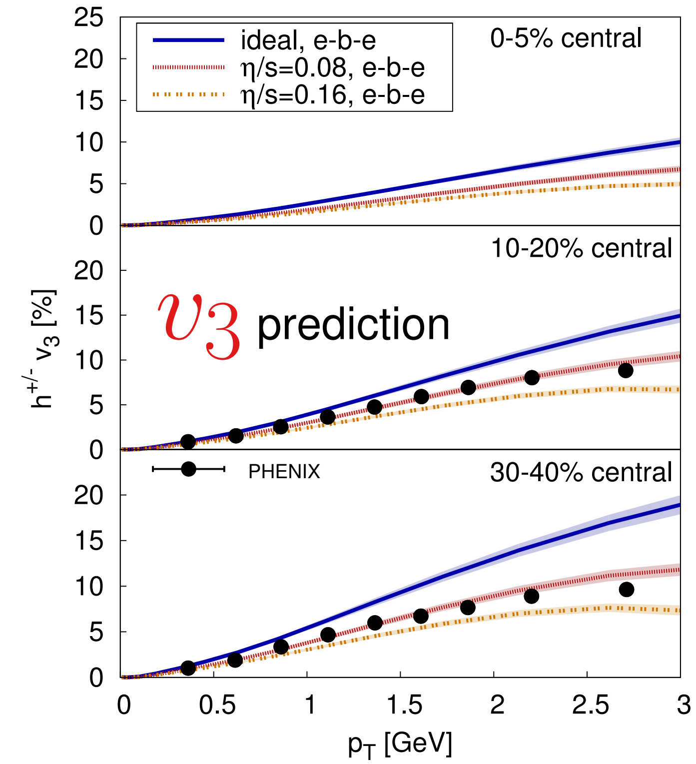
INITIAL STATE FLUCTUATIONS: A PARADIGM SHIFT IN HEAVY ION ANALYSES

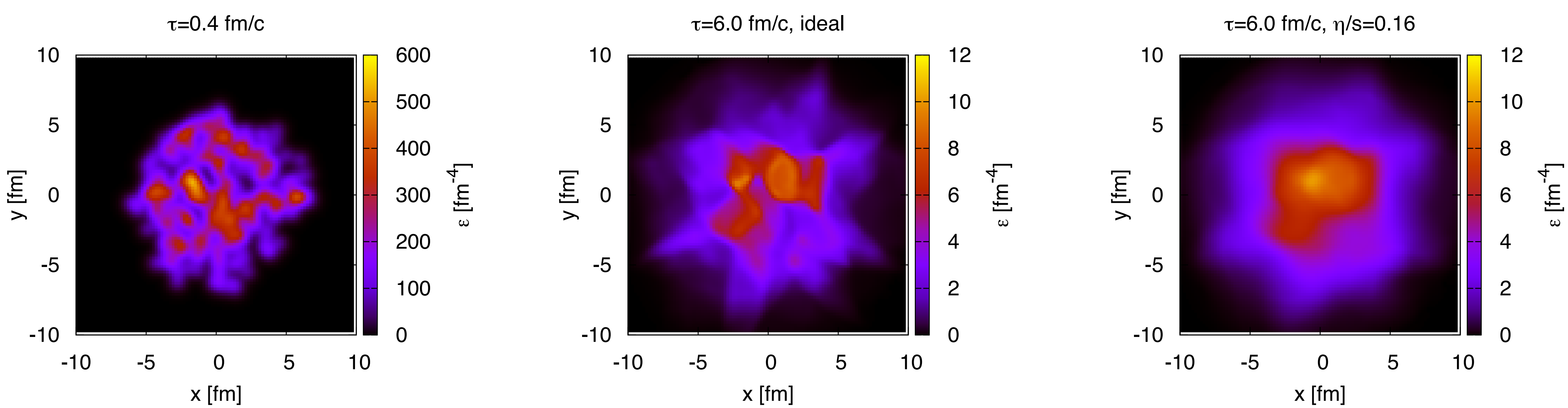
Lumpy MUSIC

(B. Schenke's talk)





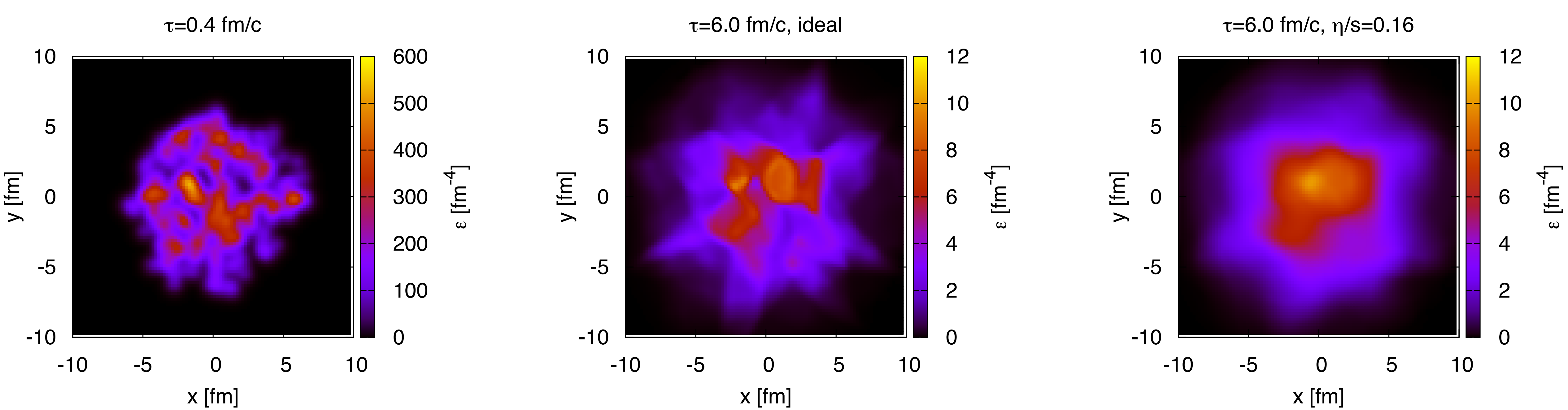




Schenke, Jeon, Gale, PRL (2011)

Initial state fluctuations: MC Glauber initialization

- Sample the nucleon locations from the nuclear density profile (with or without the shell effect deformations)
- Identify the colliding partners ($d \leq \sqrt{\sigma_{NN} / \pi}$)
- Having identified the wounded nucleons, ascribe an energy distribution at each site, with a Gaussian width σ_0 .



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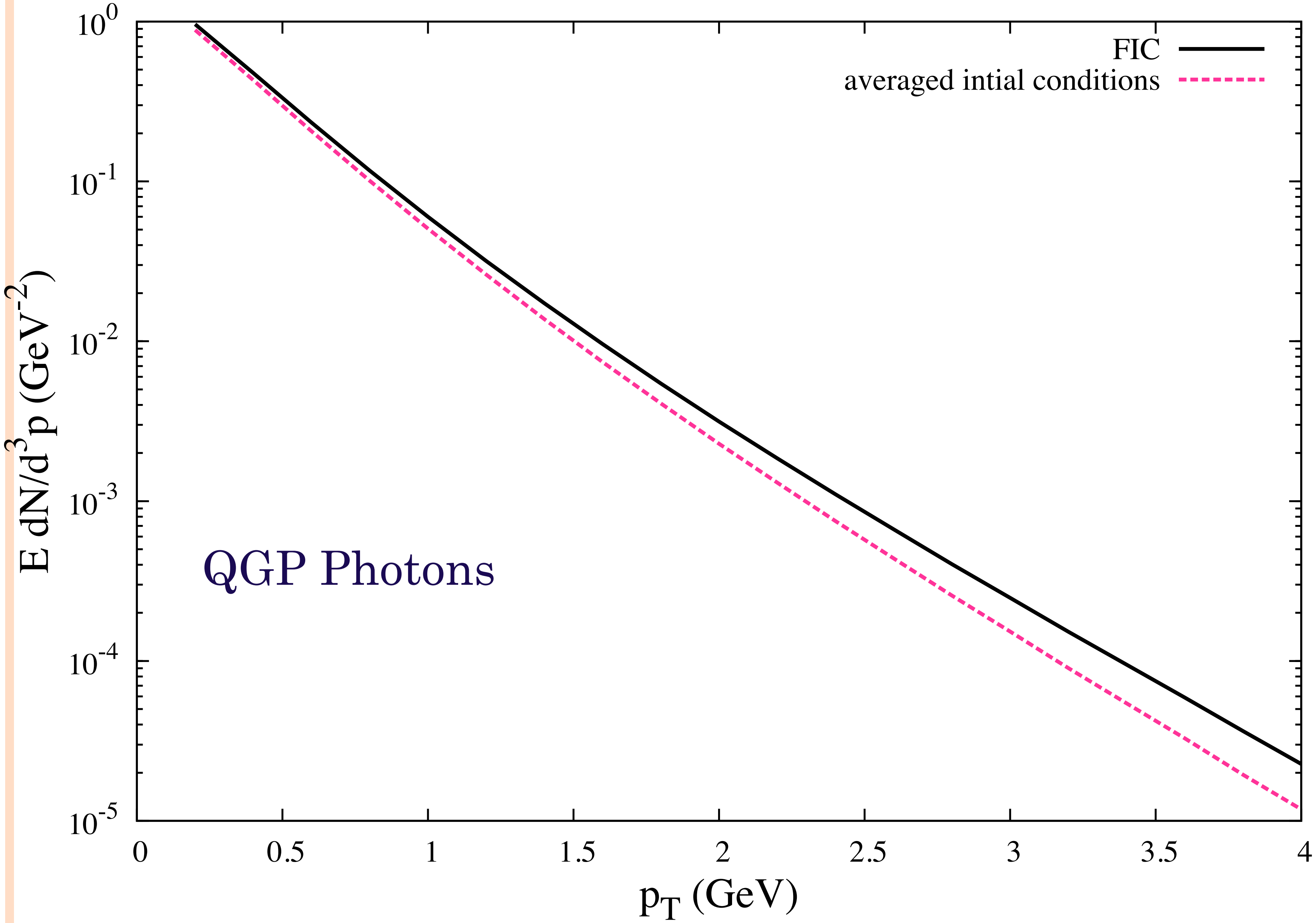
The effect on the thermal photon spectrum



- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*

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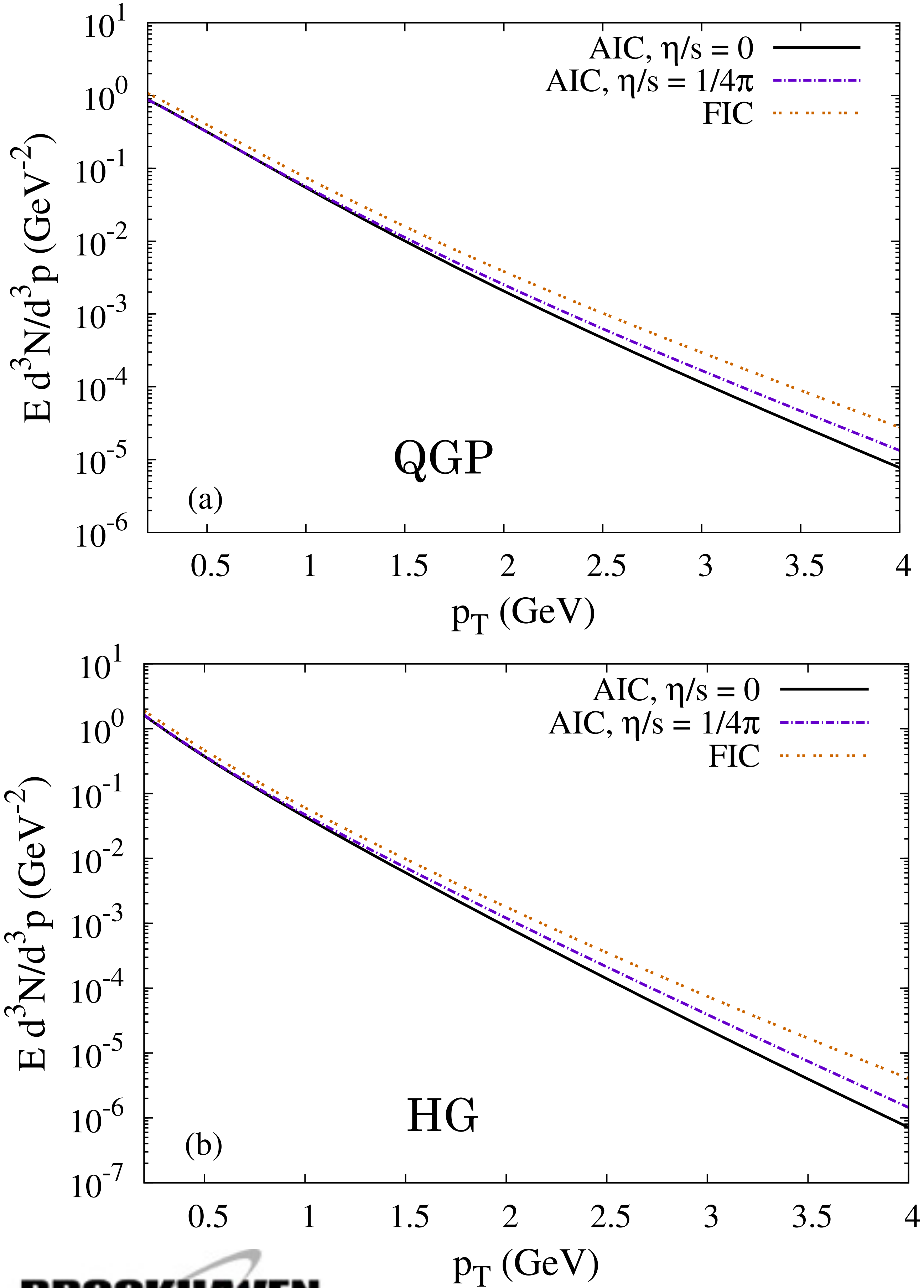
More spectrum studies



- Combined with viscous corrections, FIC yield an enhancement by ≈5 @ 4 GeV, and ≈2 @ 2 GeV
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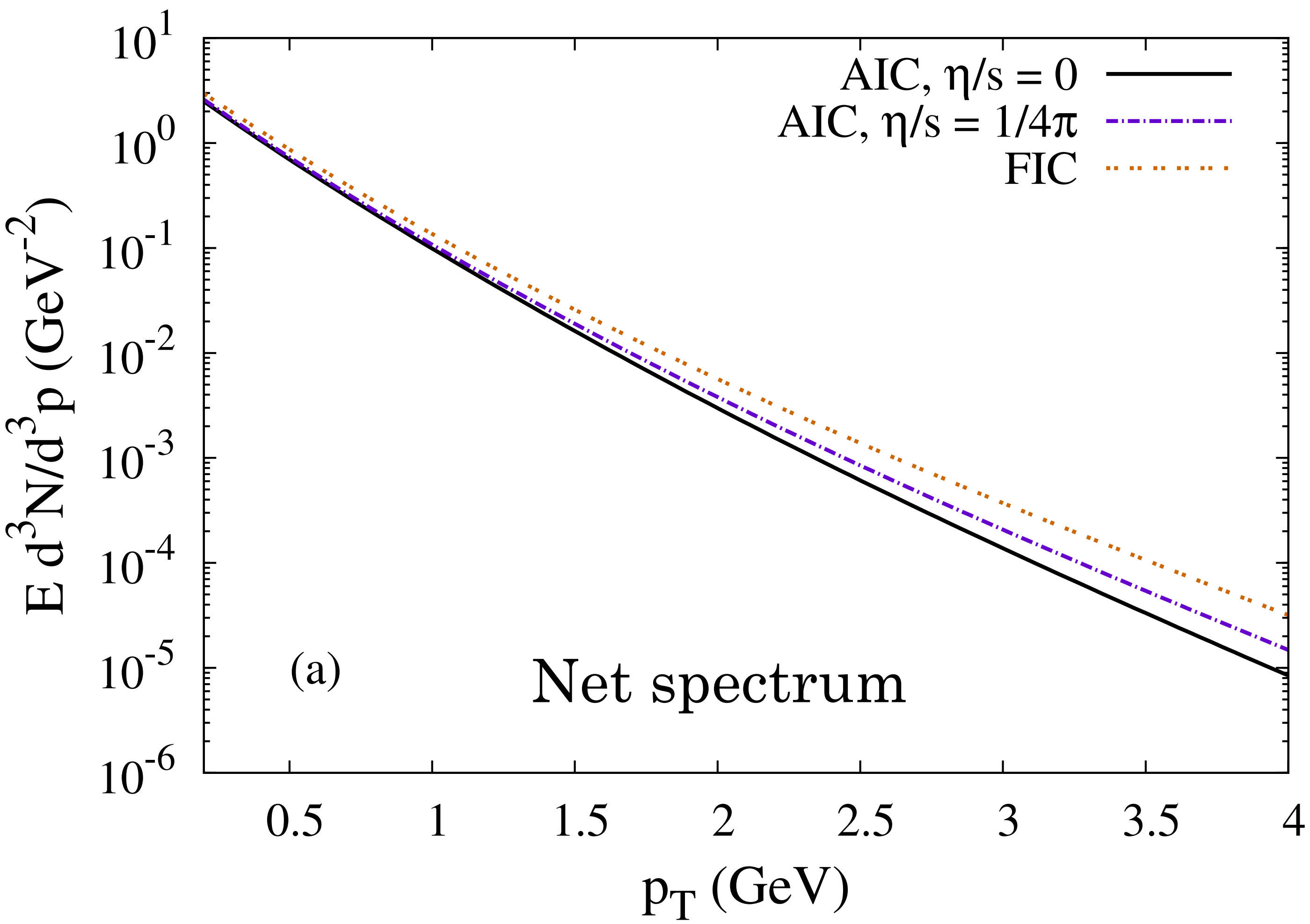

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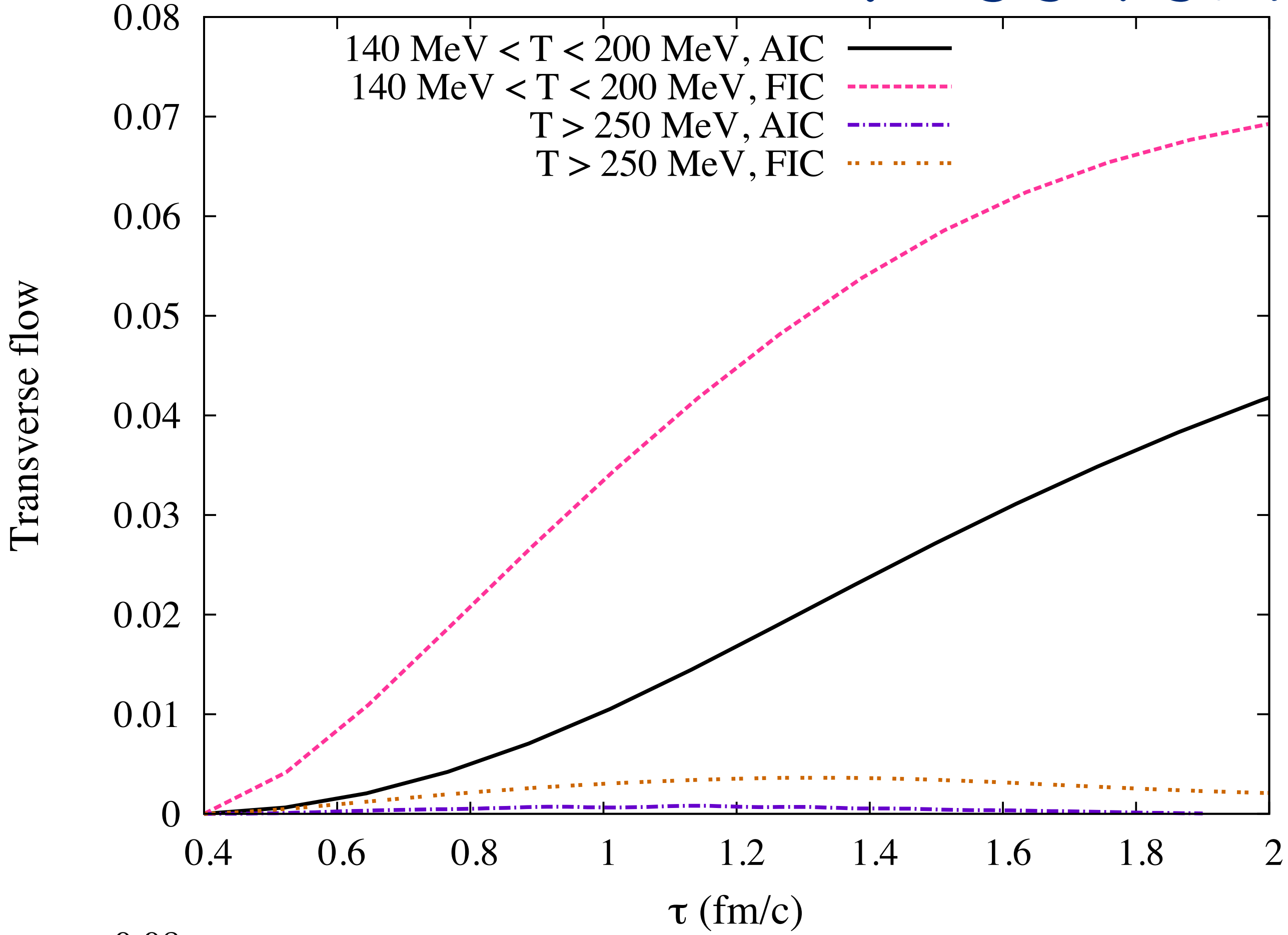
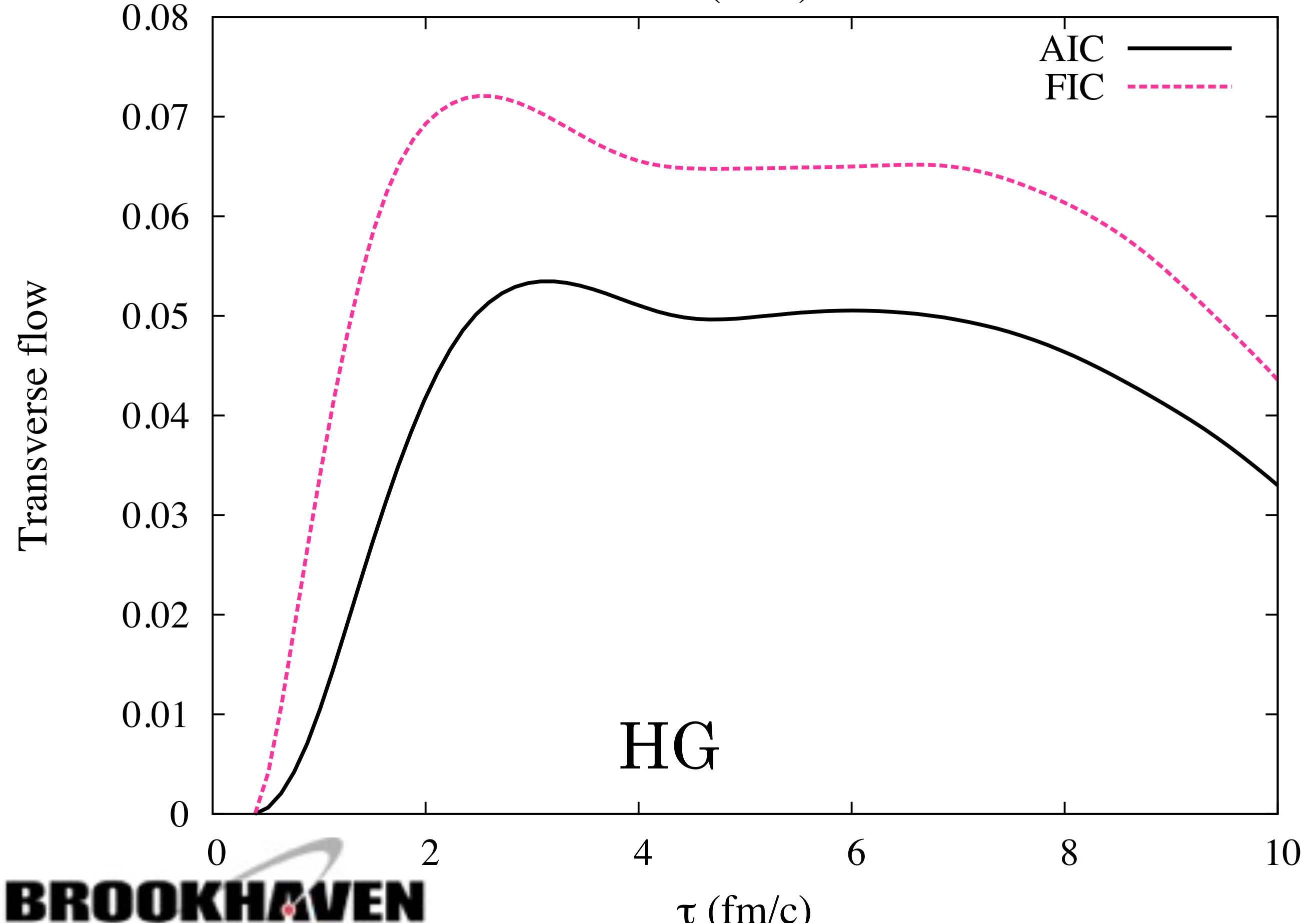
FICs vs. AICs



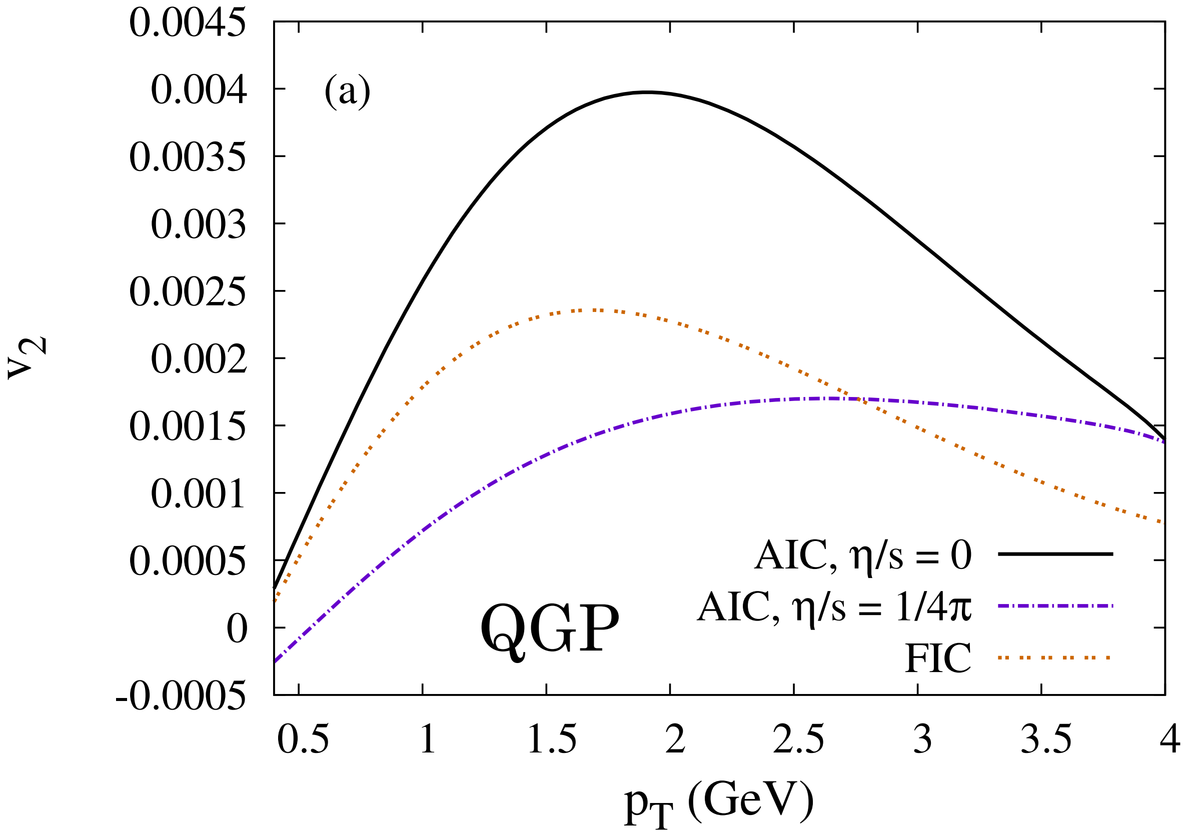


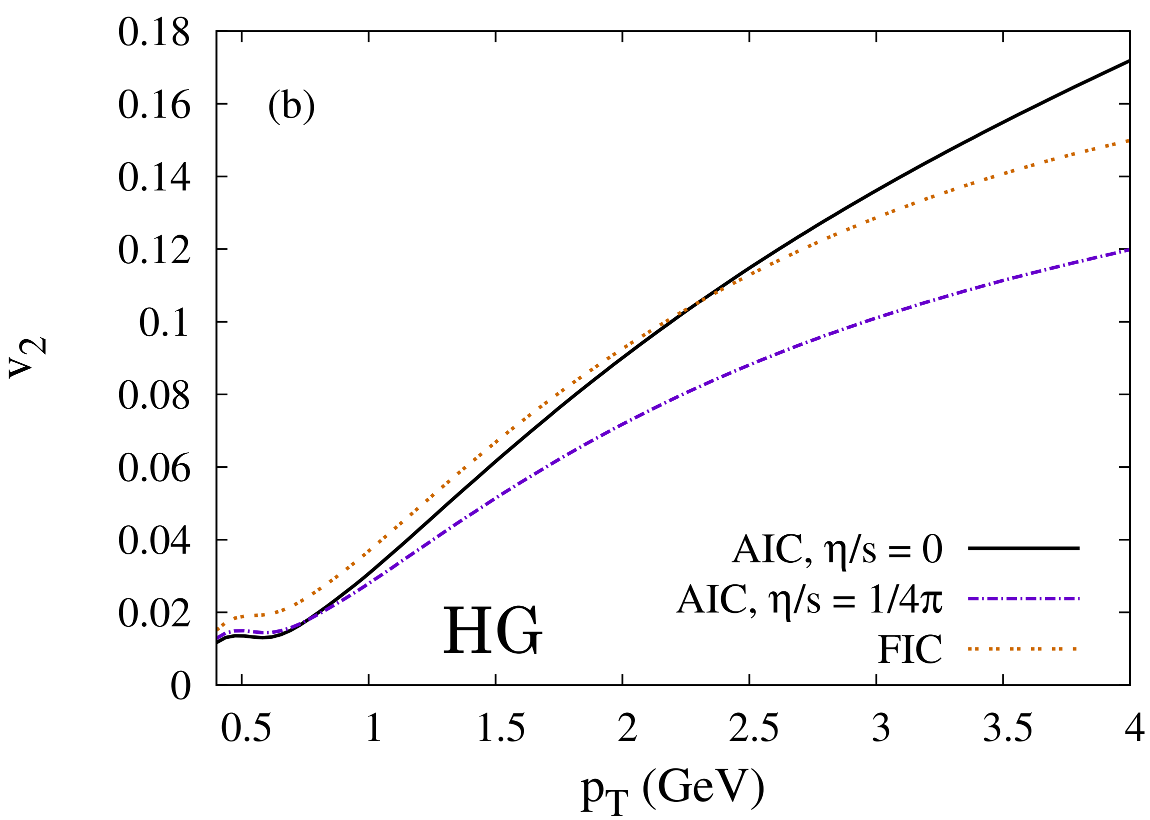
- Velocities are larger with FICs, by ≈60%
- Early times velocities are small, but still different in the two cases
- This suggest a combination of "hot spots" and of blue-shift, for generating the harder spectra with FICs.

QUANTIFYING THE EFFECT ON THE THERMAL PHOTON SPECTRUM

P_T (GeV)	Viscosity	FIC	Viscosity + FIC
1	18%	18%	41%
2	30%	45%	82%
3	30%	77%	126%

FICs and thermal photon v_2





- The combination of FICs and of viscous effects enhance v_2 in this centrality class (0-20%), as for hadrons
- For hadrons measured in events belonging to large centrality, FICs will *decrease* v_2
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average. Shapes are also different, as before

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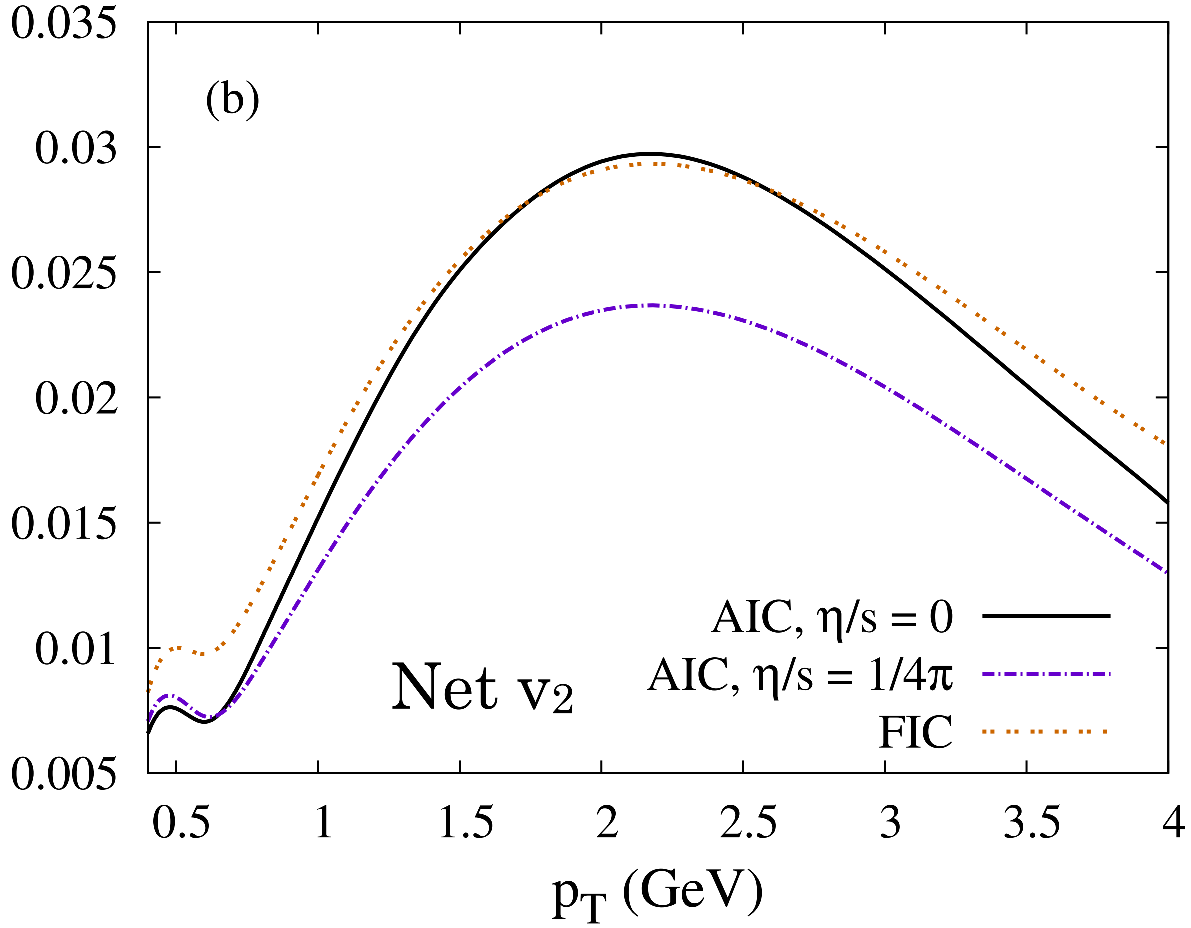

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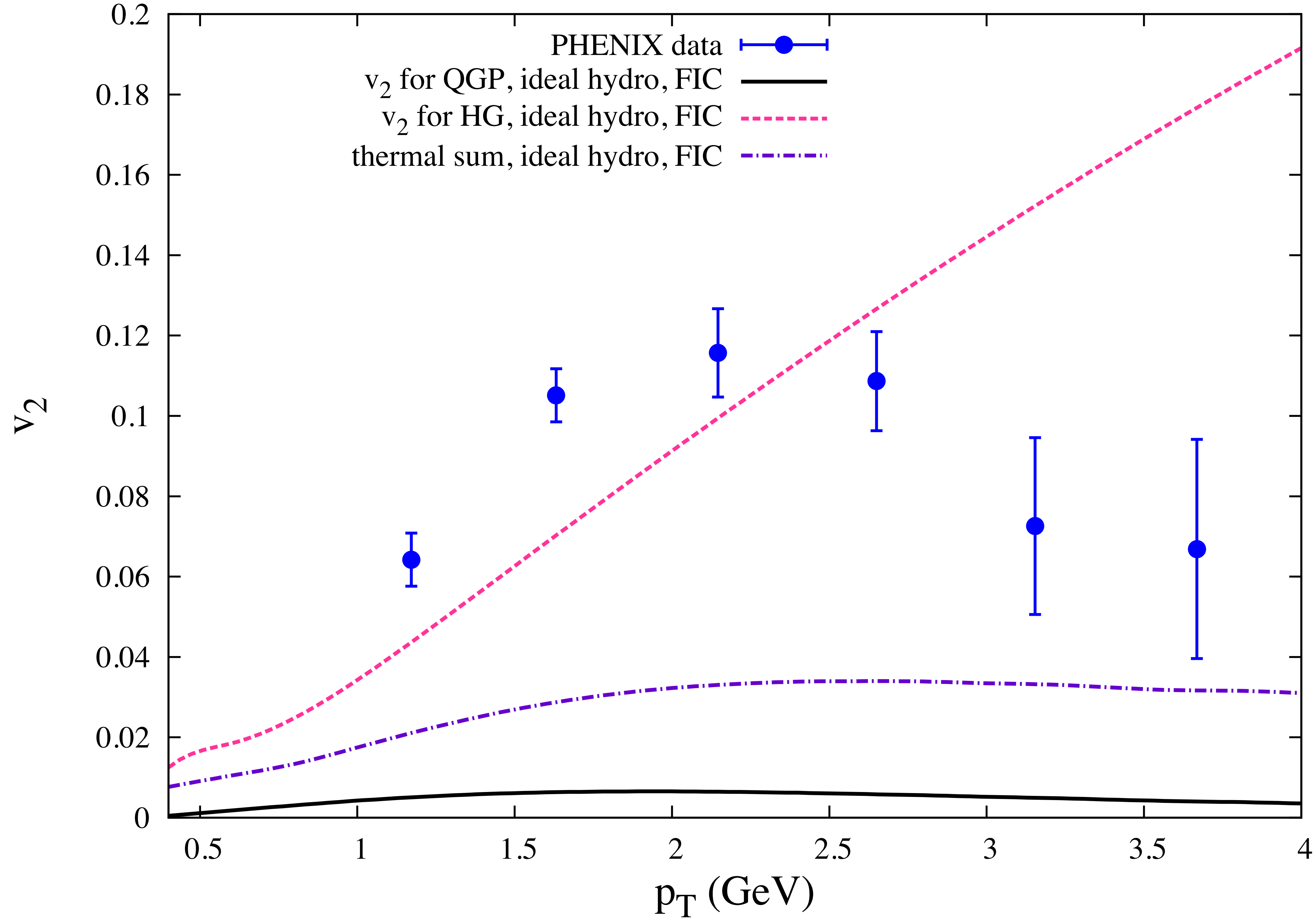
- HG elliptic flow is much larger than QGP elliptic flow, but remember net v_2 is a weighted average. Shapes are also different, as before
- Net v_2 is comparable in size to that with ideal medium. Bending down is QGP-driven

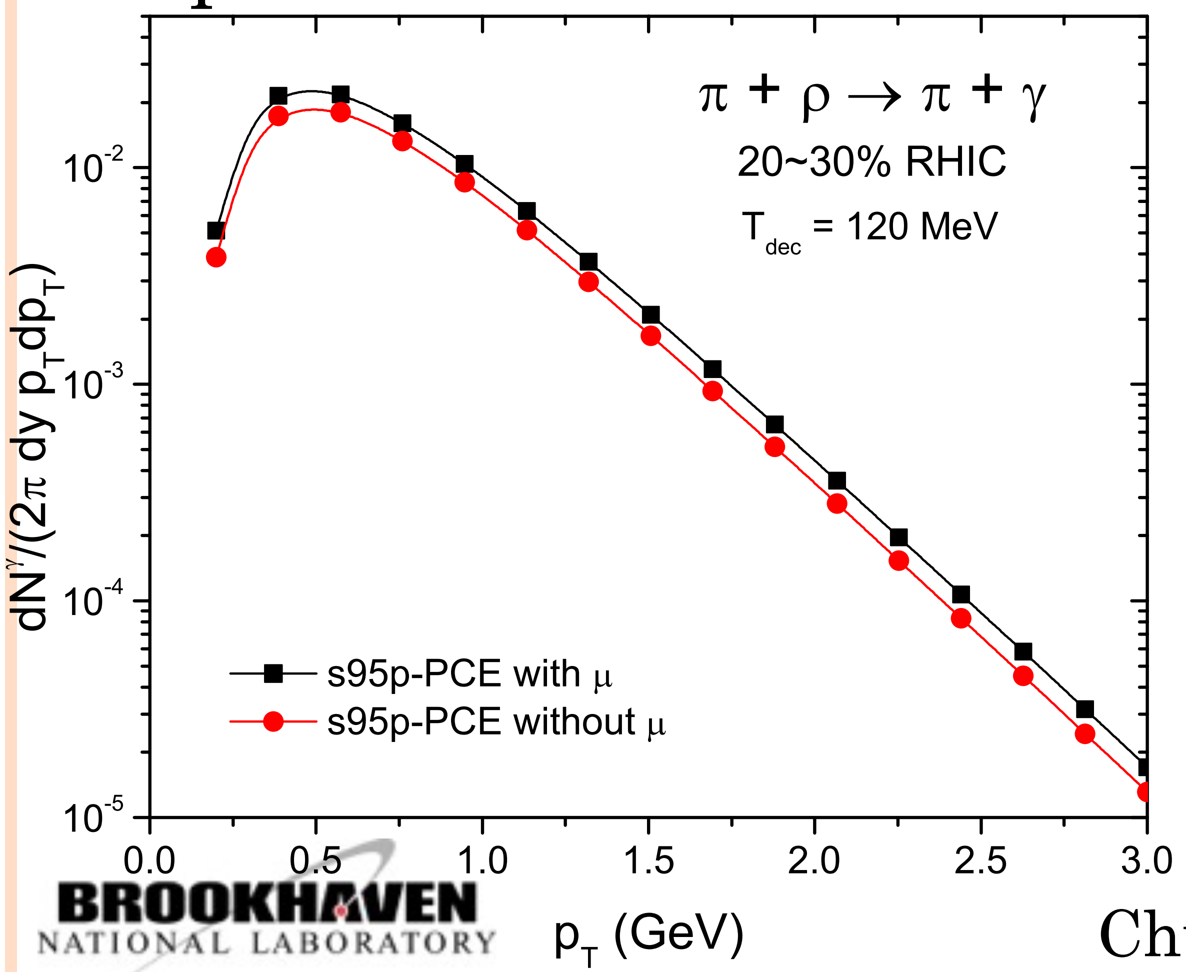
Photon v_2 Data?

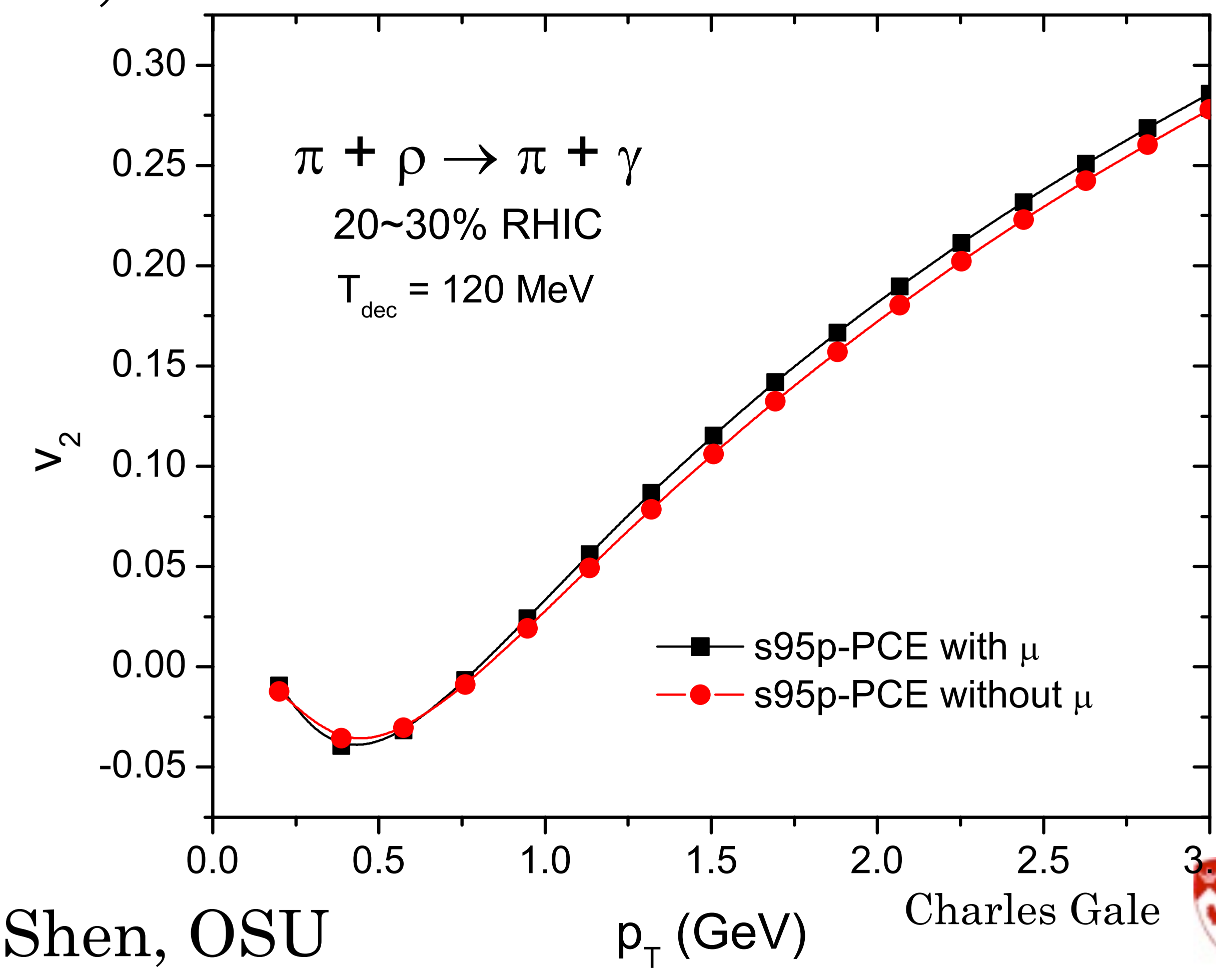


- New data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2, but shape is wrong

Some facts and some things to try

- FICs are here to stay
- Change hydro initialization and parameters. This requires consistency with the hadronic data
- Making the QGP signal larger will *decrease* the v_2. Including the T=0 photons, will decrease v_2
- Non-zero initial shear tensor
- The HG sector: A consistent treatment of chemical potentials is needed. However,





Chun Shen, OSU

What about dileptons?
Thermal dilepton elliptic flow

$$v_2(M, p_T, b) = \frac{\int d\phi \cos(2\phi) \frac{d^4N}{dM^2 dy\, p_T dp_T d\phi}}{\int d\phi \frac{d^4N}{dM^2 dy\, p_T dp_T d\phi}}$$

Chatterjee, Srivastava, Heinz, Gale, PRC (2007)

- Additional degree of freedom: M and p_T may be varied independently

THERMAL DILEPTON SOURCES

- QGP: Born term $q\bar{q} \rightarrow \ell^+ \ell^-$
- HG contribution: calculate the in-medium vector spectral density

$$\Pi_{ab}(E,p) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_b(\omega) \frac{\sqrt{s}}{\omega} f_{ab}^{\text{c.m.}}(s)$$

- Vector mesons scatter off hadrons. Spectral density is distorted

Eletsky and Ioffe, PRL (1997)
Eletsky and Kapusta, PRC (1999)

Resonance	Mass (GeV)	Width (GeV)	Branching ratio
N(2190)	2.127	0.547	0.29
N(2100)	1.885	0.113	0.27
N(2090)	1.928	0.414	0.49
N(2080)	1.804	0.447	0.26
N(2000)	1.903	0.494	0.60
N(1900)	1.879	0.498	0.44
N(1720)	1.717	0.383	0.87
N(1700)	1.737	0.249	0.13
N(1520)	1.520	0.115	0.0040
Δ(2000)	1.752	0.251	0.22
Δ(1940)	2.057	0.460	0.35
Δ(1905)	1.881	0.327	0.86
Δ(1900)	1.920	0.263	0.38
Δ(1700)	1.762	0.599	0.08
Δ(1232)	1.232	0.118	0.0055

ϕ :Vujanovic and Gale, PRC (2009)

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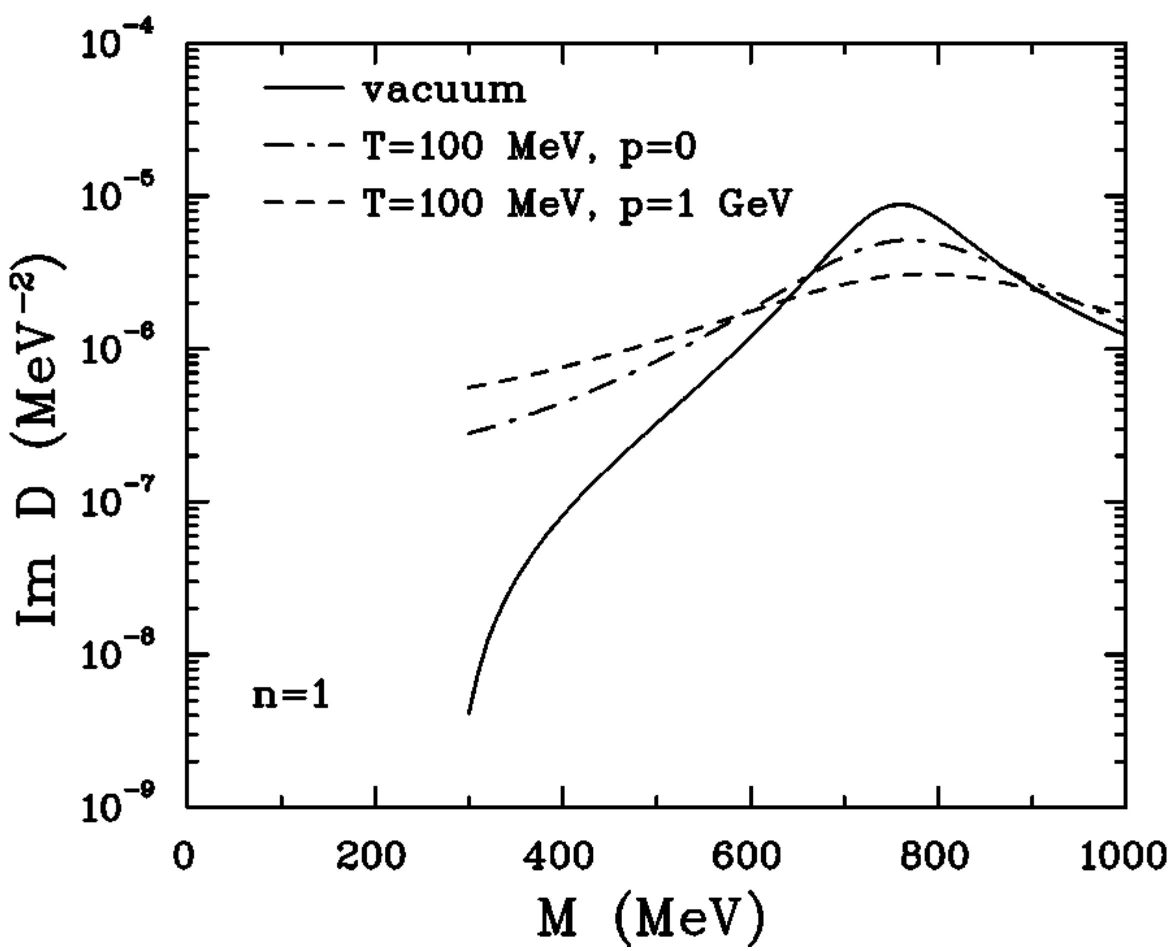

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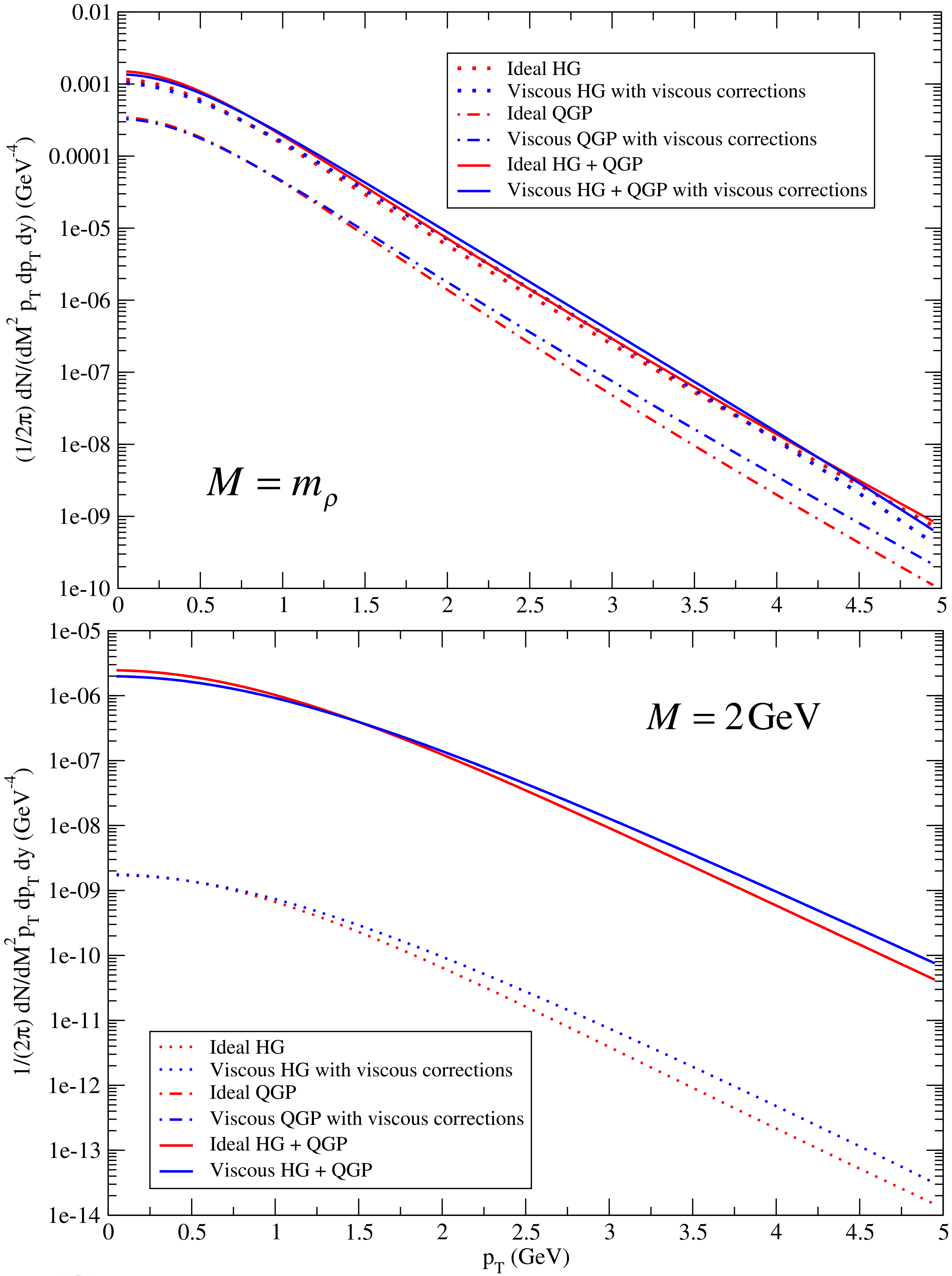
Thermal dilepton spectra: some results

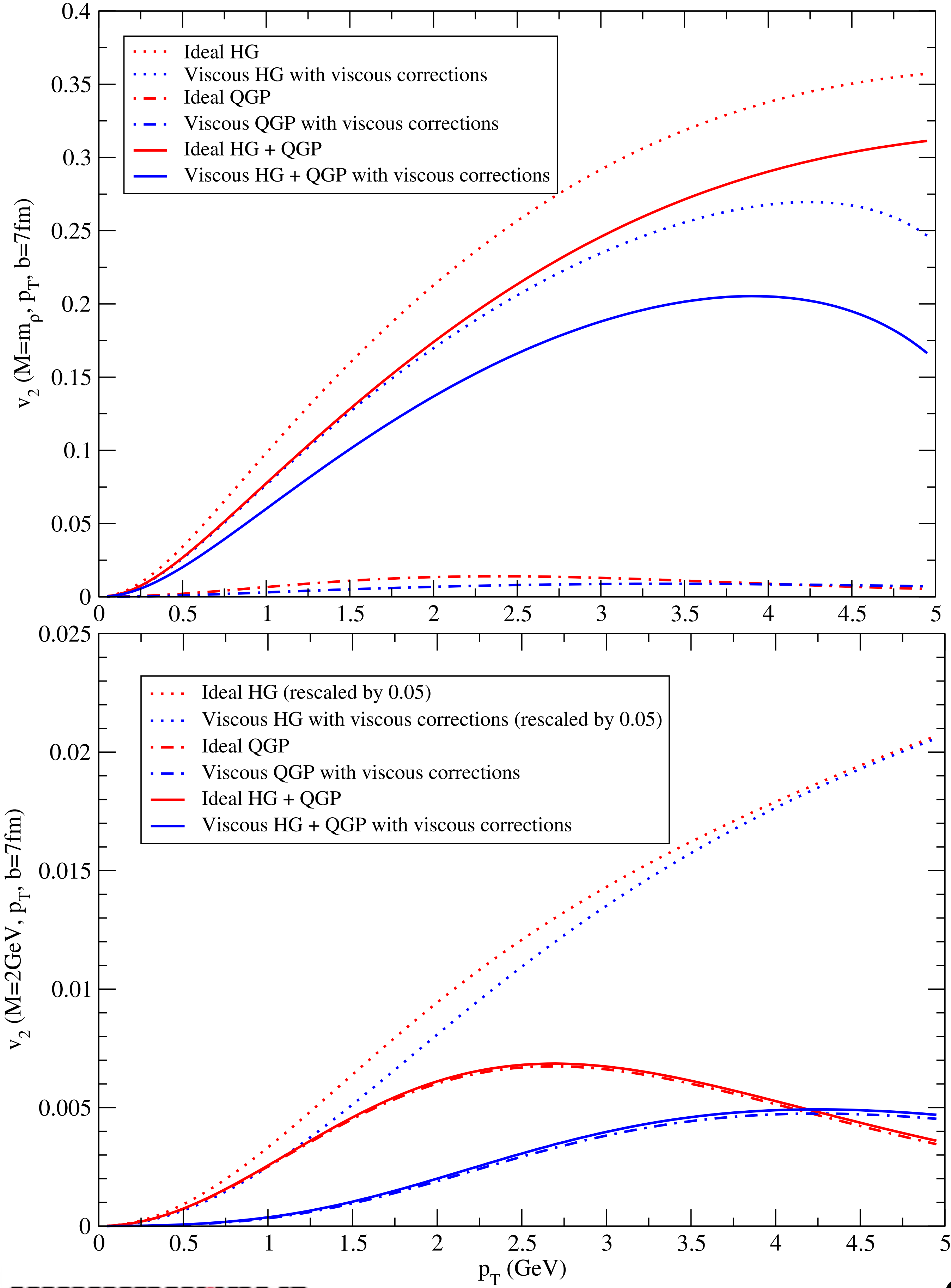


- Transition from HG-dominated to QGP-dominated
- $D\bar{D}$ not included here
- Effects of viscous corrections are modest

  c.f. Dusling & Lin, NPA (2008)
- Same hydro as for photon calculations

G. Vujanovic, 2011

Thermal dilepton v_2 with viscous effects



- Low M: HG-dominated
- High-M: QGP dominated

  Chatterjee, Srivastava, Heinz, Gale PRC (2007)

- No open charm here
- v_2 as a function of M will contain some info on the transition regime
- Viscous effects are modest
- FICs? Coming soon...

G. Vujanovic, 2011

Conclusions

Work done with:

- Maxime Dion
- Jean-François Paquet
- Gojko Vujanovic
- Björn Schenke
- Clint Young
- Sangyong Jeon

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